Superconducting Devices for Millimeter through Far-Infrared Detection

Jonas Zmuidzinas

Caltech

CALTECH

Superconducting Devices

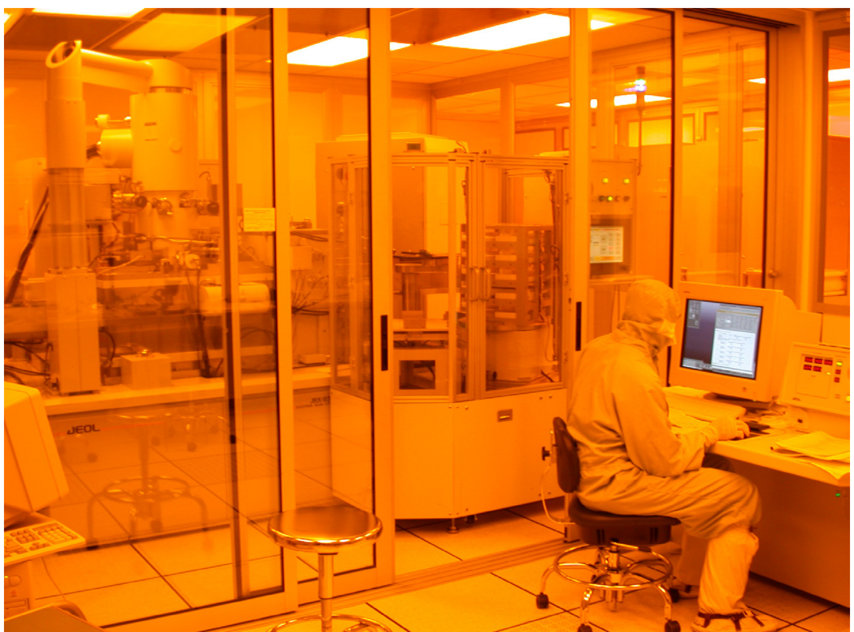
Caltech/JPL superconducting detector group

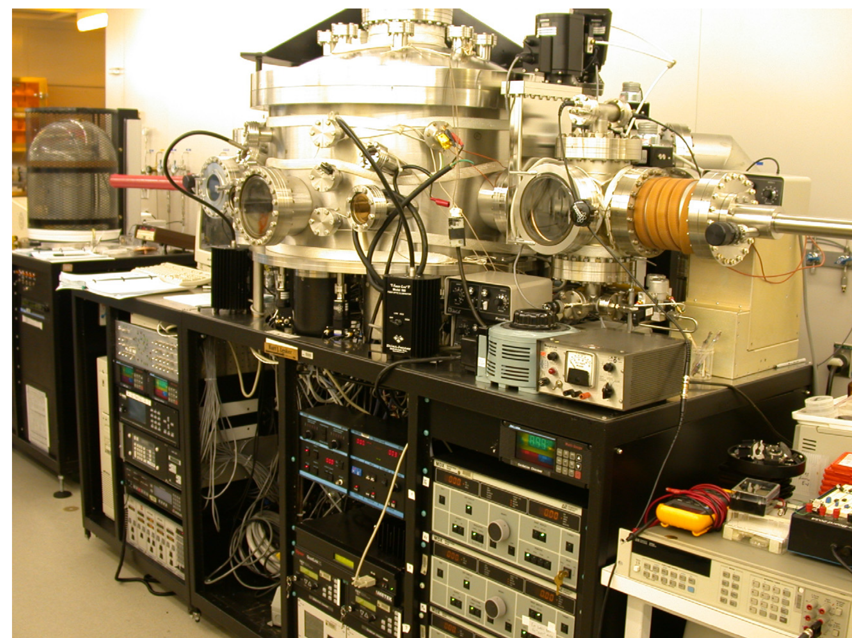
Jamie Bock	JPL/Caltech	Bolometers, TES, Antennas…
Peter Day	JPL (CIT Ph.D.)	KIDs, TES
Megan Eckart	Ph.D. student	KIDs, X-ray applications
Jiansong Gao	Ph.D. student	KID device physics
Alexey Goldin	JPL	Array antennas, filters
Sunil Golwala	Professor	Sunyaev-Zeldovich, dark matter
Fiona Harrison	Professor	KIDs, X-ray applications
Cynthia Hunt	Ph.D. '03	Twin-slot TES
Shwetank Kumar	Ph.D. student	KIDs
Chao-Lin Kuo	JPL	Antenna-coupled TES
Andrew Lange	Professor	CMB applications
Rick LeDuc	JPL	Low-Tc Group Leader
Chris Martin	Professor	KIDs, UV/optical applications
Peter Mason	CIT/JPL (retired)	Cryogenics, KIDs
Ben Mazin	Ph.D. student	KIDs, UV/optical applications
Tom Phillips	Professor	SIS mixers
Jeff Stern	JPL (CIT Ph.D.)	mm-wave modulator
Tasos Vayonakis	Ph.D. student	Microstrips, antennas, KIDs
Minhee Yun	JPL	Antenna-coupled TES
Jonas Zmuidzinas	Professor	KIDs, antennas, etc.

Superconducting Devices

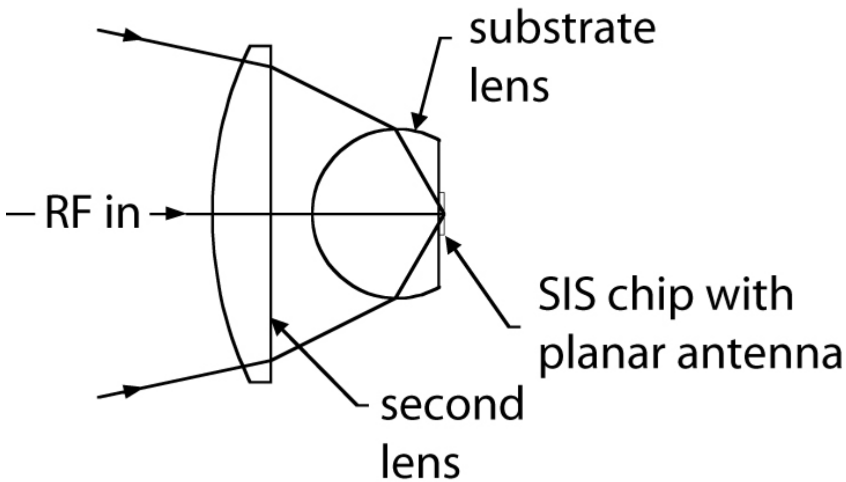
JPL's Microdevices Laboratory

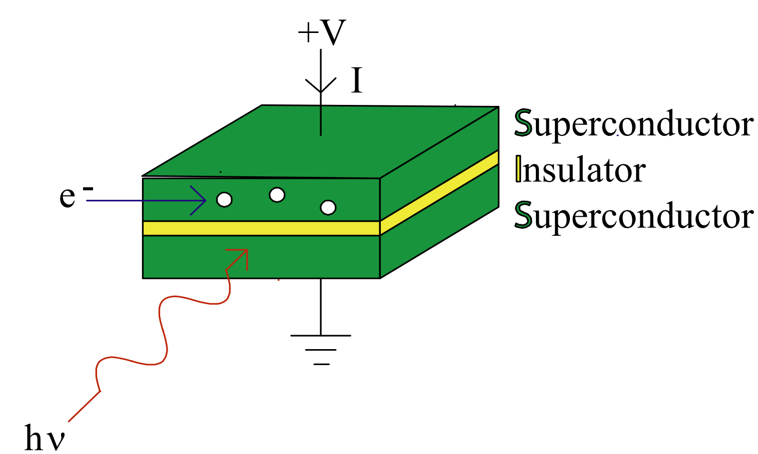
- 38,000 sq. ft. facility
- Class 10 to 100,000 cleanrooms
- Dedicated equipment for superconducting devices
- E-beam & UV stepper lithography
- Completed in late 1980's
- Detectors: one of original thrusts

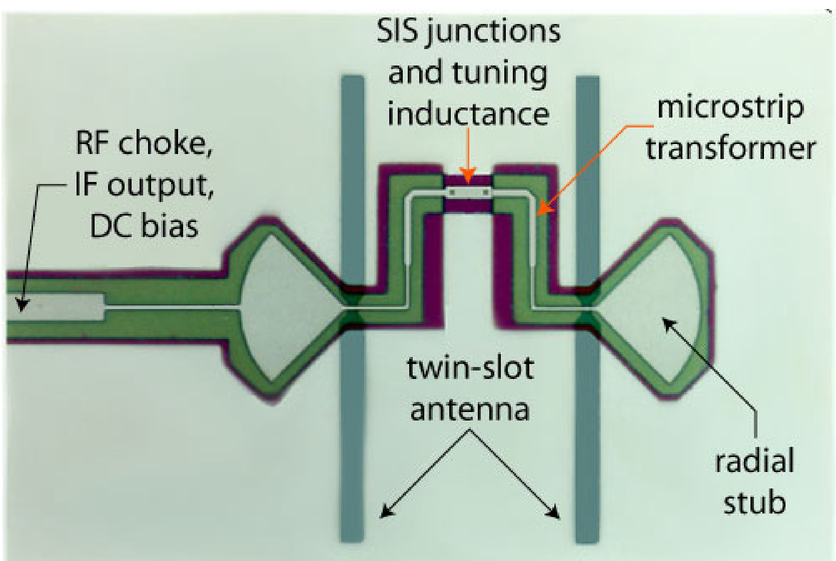




Superconducting tunnel junction (SIS) mixers







- co-invented by Prof. T. Phillips
- “photodiode” for mm/submm
- SIS mixers in development at JPL/Caltech since early 1980’s
- established JPL capability in superconducting devices

CALTECH

Superconducting Devices

SIS mixer applications (mm/submm)

CSO

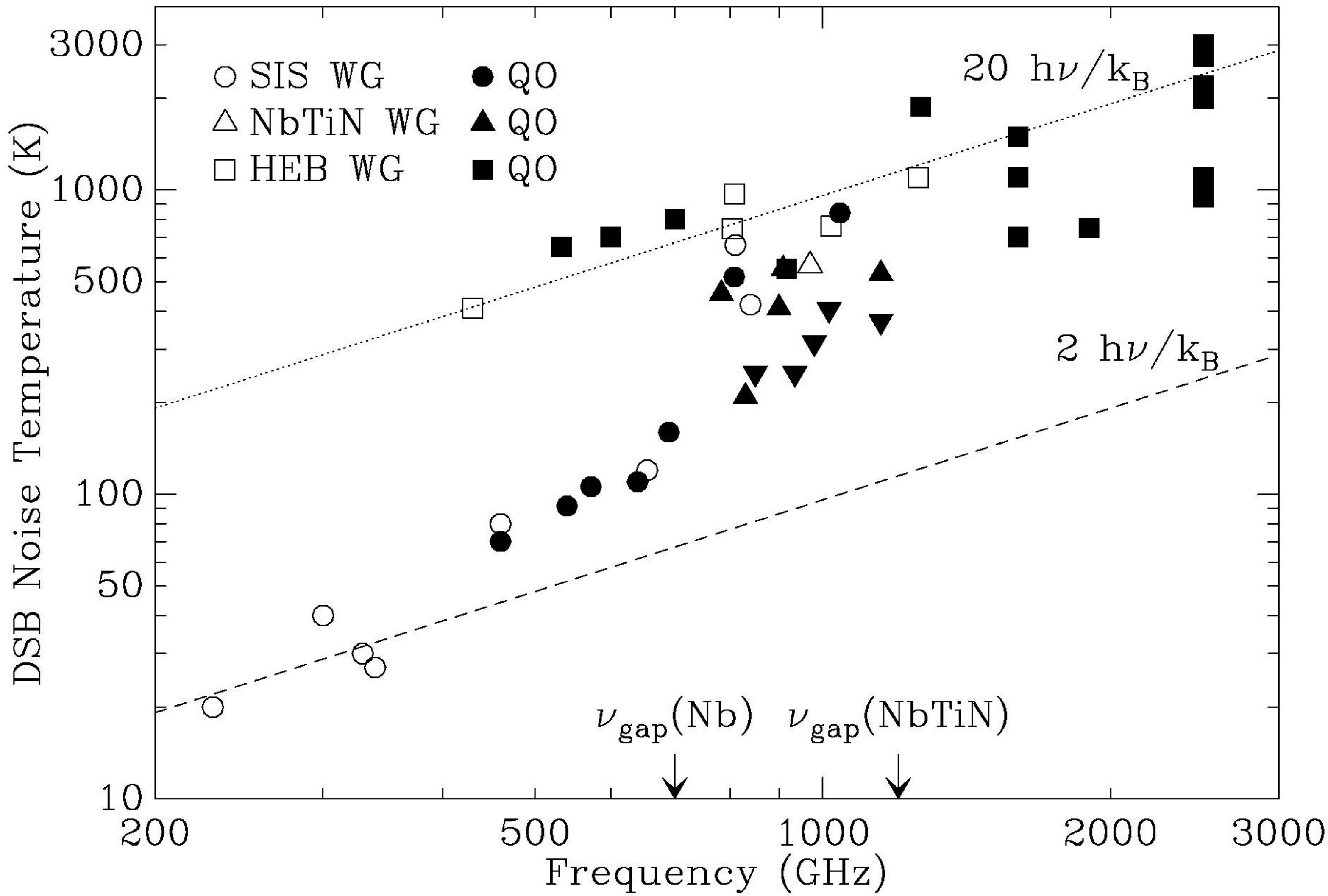
OVRO/
CARMA

Herschel

SOFIA

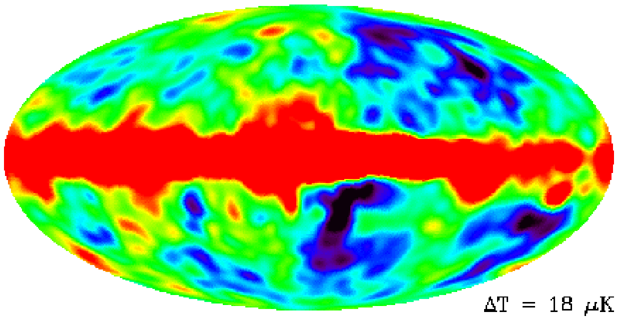
+ ALMA…

Noise Temperatures

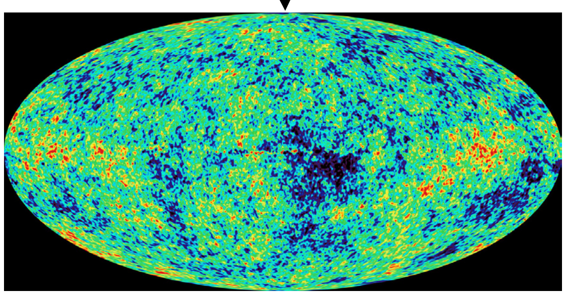


The sensitivity increase required

COBE



×40

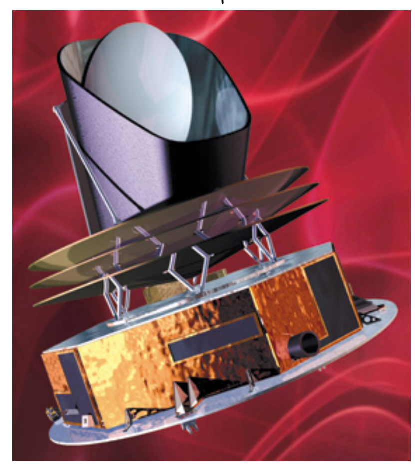


WMAP (HEMT)

×20†

CMBPol

×20-100 ?



Planck (bolometers)

† Specifications; mission-realized sensitivity expected to be better.

WMAP and Planck benefit from better detectors, but Planck will be close to the background limit

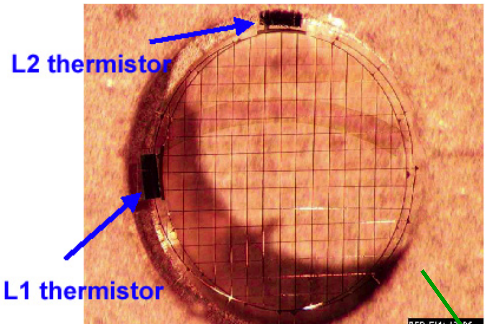
Credit: S. Church

CALTECH

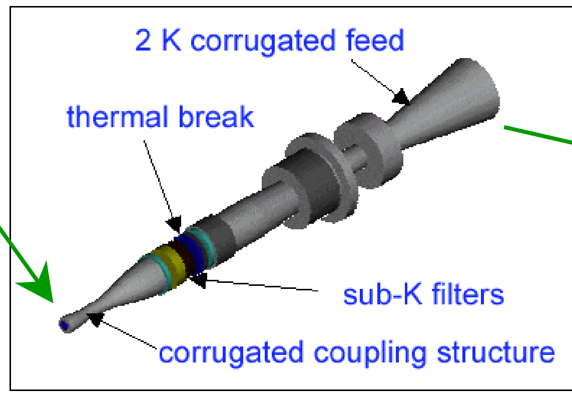
Superconducting Devices

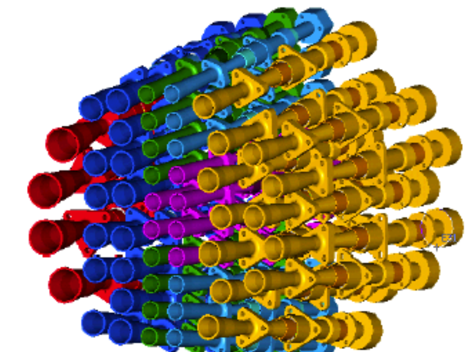
Planck HFI

- 50 feeds, ~ 1kg at 100mK
- Area ~ 2 square degrees
- Instantaneous coverage per polarization-sensitive band: ~0.1 square degrees



The first pair of PSBs




Planck HFI Focal Plane

Frequency (GHz)	Beam (arcmin)	No of feeds per Q (or U)	Sensitivity to Q or U (μK $s^{1/2}$)		
			HFI spec	CMB + Inst. BLIP	CMB BLIP
143	7	2	170	41	23
217	5	2	250	58	26
353	5	2	780	162	37

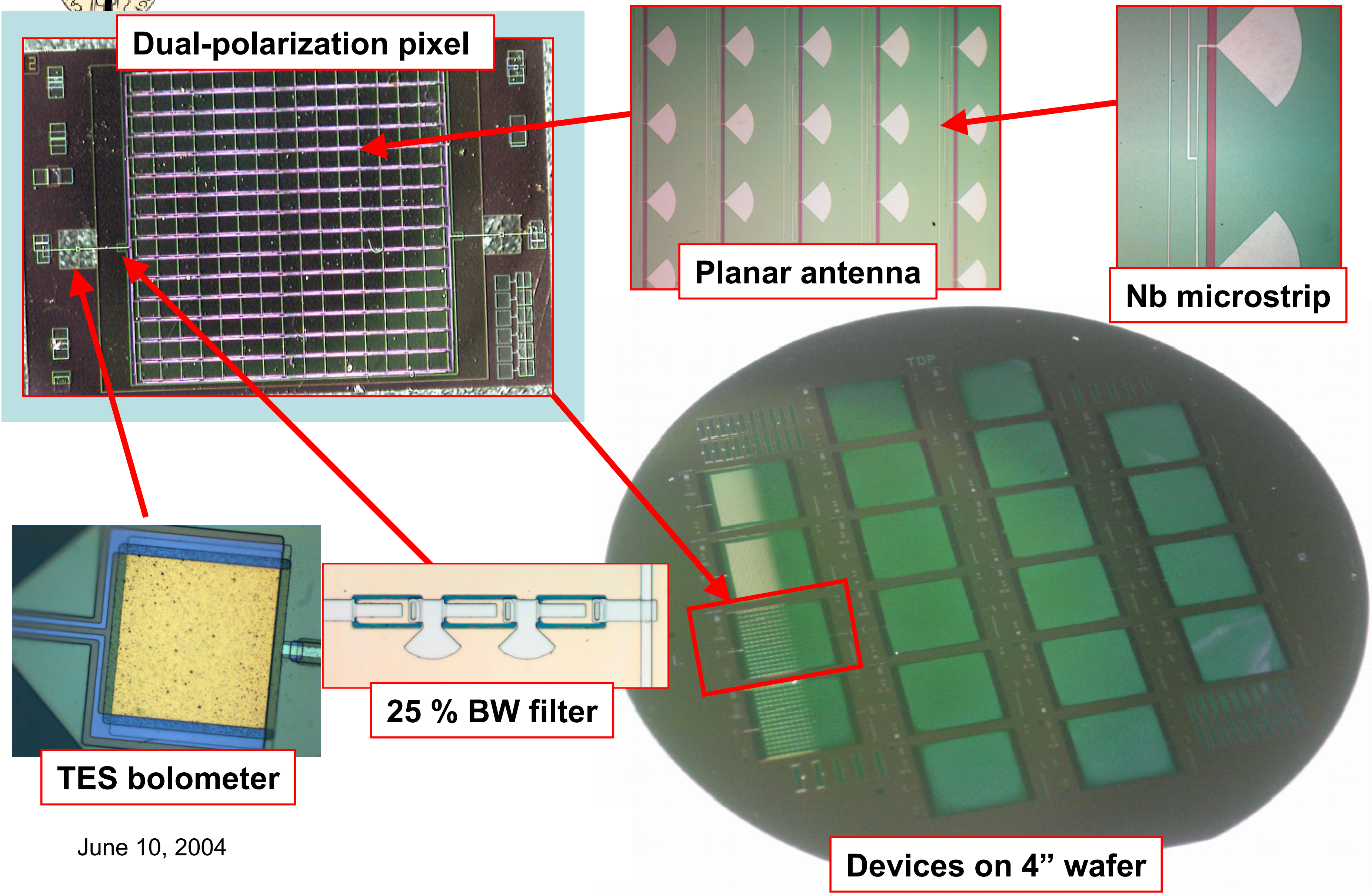
Also: 100, 545 and 850 GHz channels, not polarization sensitive

Credit: S. Church

How to make a larger CMB focal plane ?

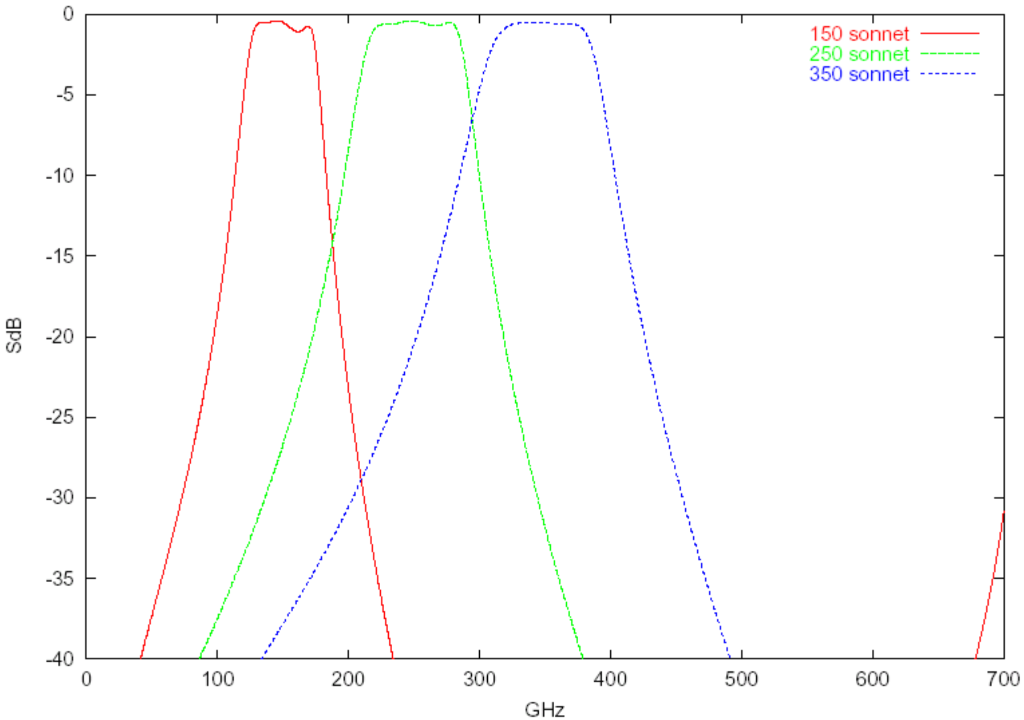
- HFI already near background limit!
- Use more detectors ($20^2 = 400$)
  - Volume, mass, wiring, …
- Need more efficient use of focal-plane area
- Want “CCD-like” arrays
- Use lithography as much as possible
- Planar antennas instead of horns
- Integrate functionality
  - Antennas
  - Filters
  - Detectors
  - Modulation
- Detector multiplexing !

Antenna-coupled superconducting bolometers



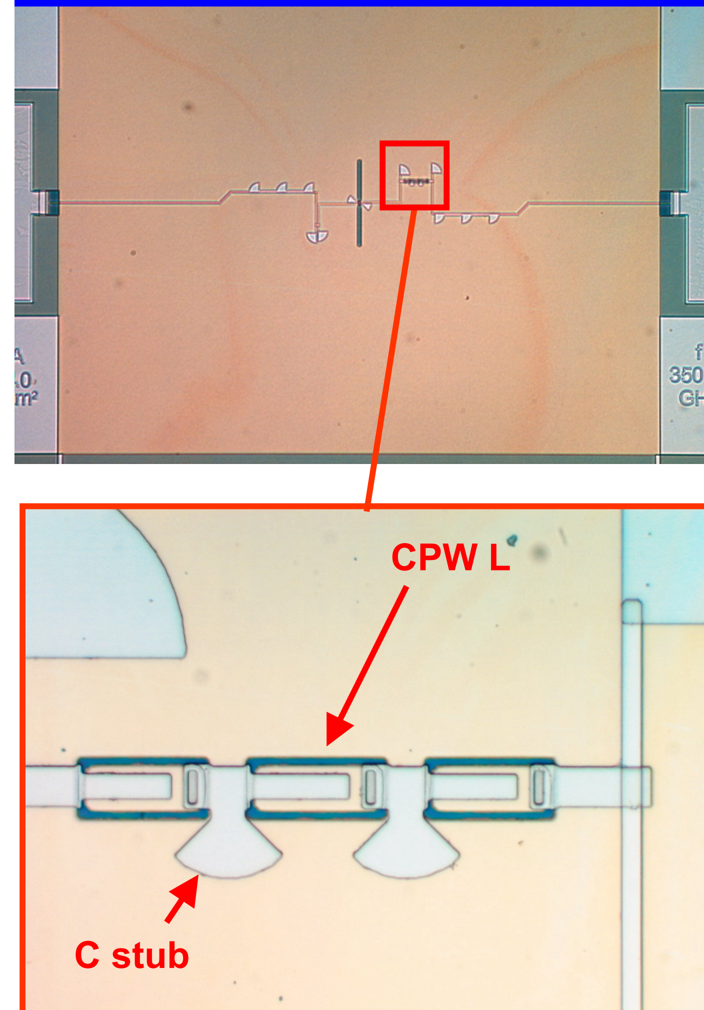
Lumped-Element MM-wave Filters

Calculated Transmittance



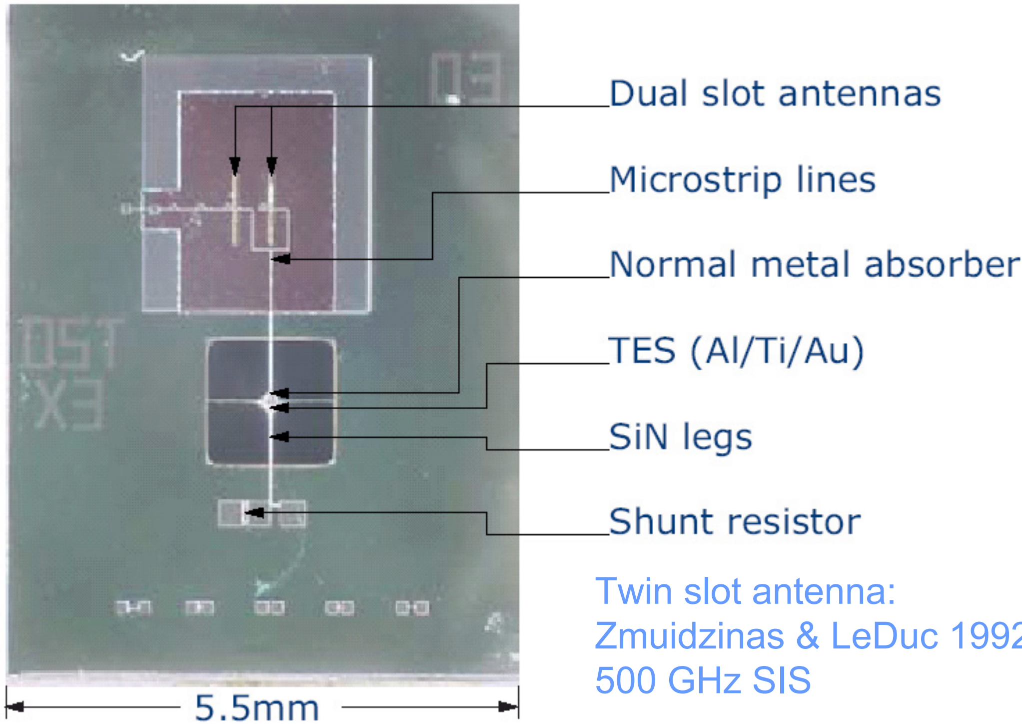
- **3-pole lumped-element filter**
- **calculation using Supermix and Sonnet**
- **designed for multichannel applications**

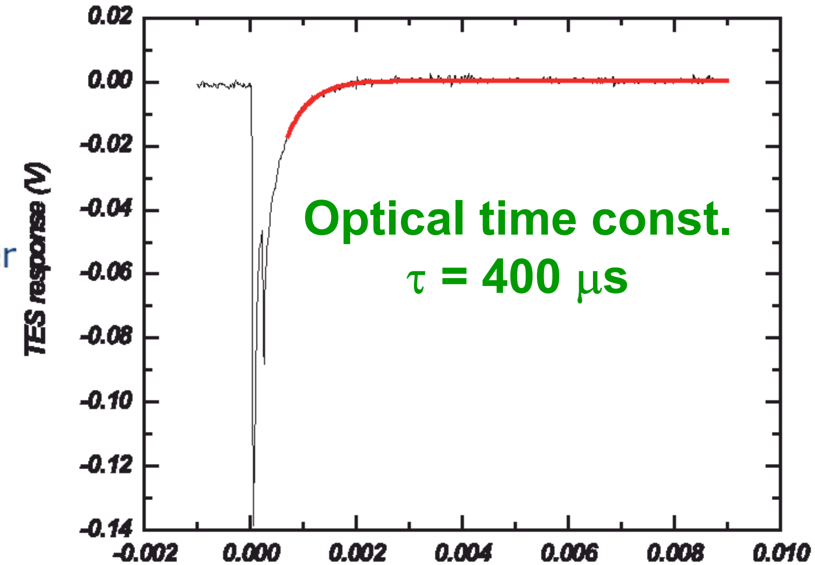
Sample for Filter Test



Goldin et al. (2002)

Demonstration of Antenna-Coupled TES

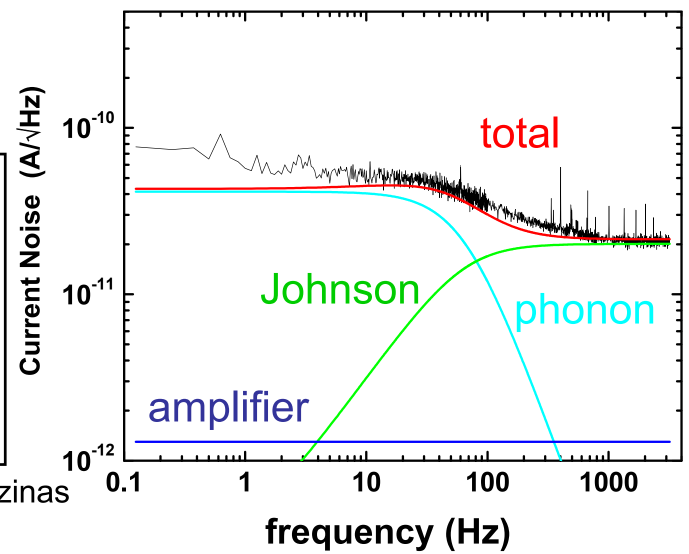




Twin slot antenna:
Zmuidzinas & LeDuc 1992
500 GHz SIS

NOTE: twin-slot needs substrate lens

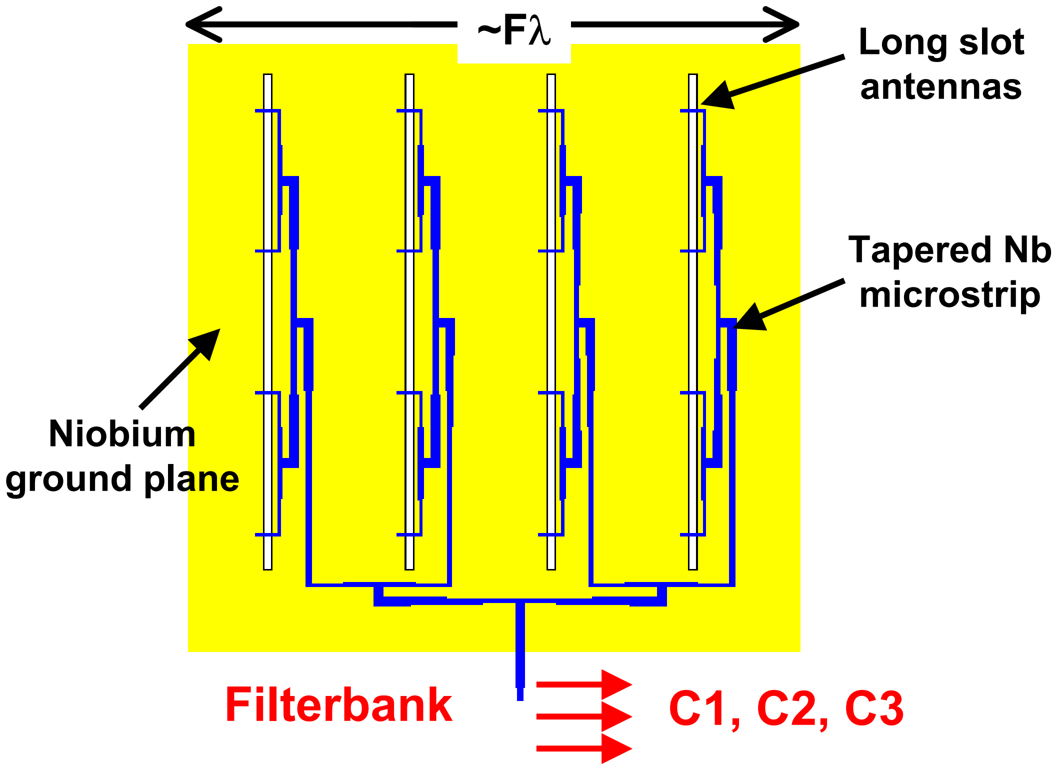
NEP = 1.8 e-17 W/√Hz
τ = 400 μs
NEP $\sqrt{\tau}$ = 4 e-19 J
T_0 = 300 mK
High optical efficiency



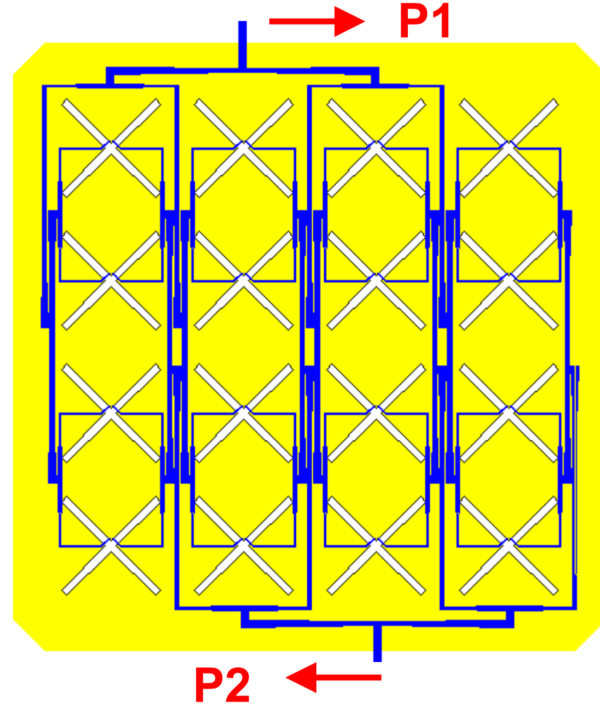
C. Hunt et al. (2003)

Narrow-beam planar antennas

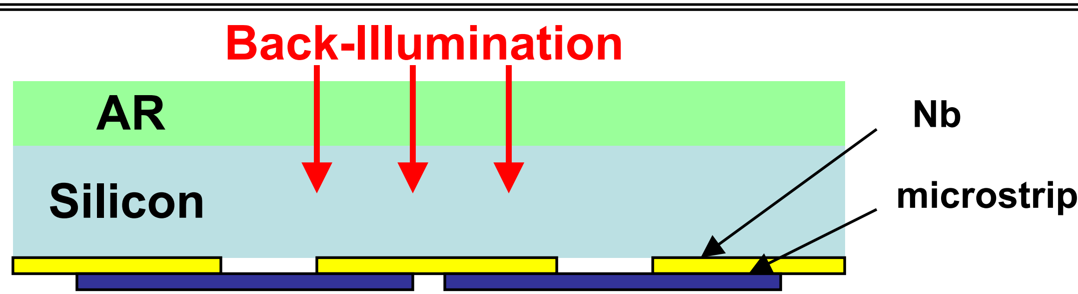
Multi-band, single pol



Single band, dual pol



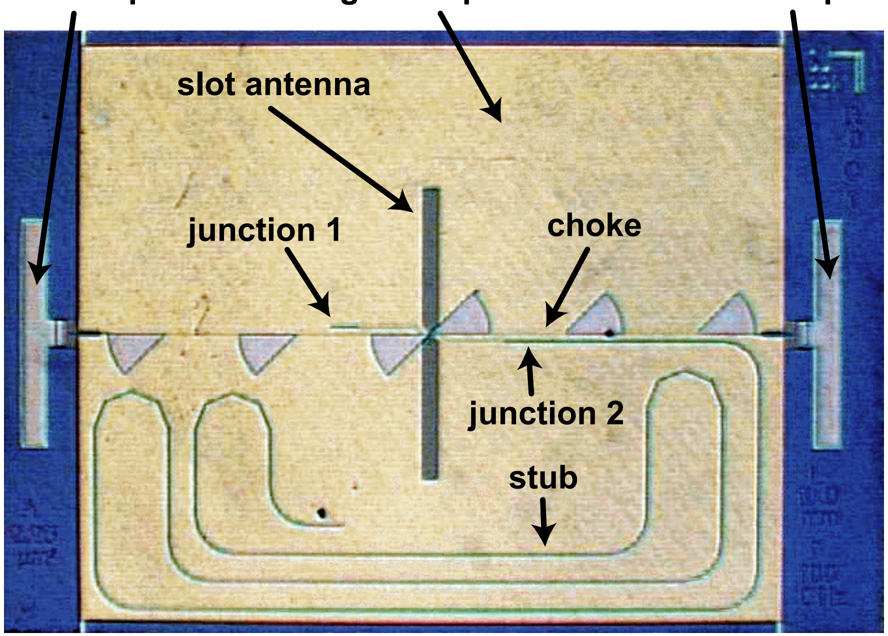
F ~ 3 feasible ! (since microstrip loss is low)

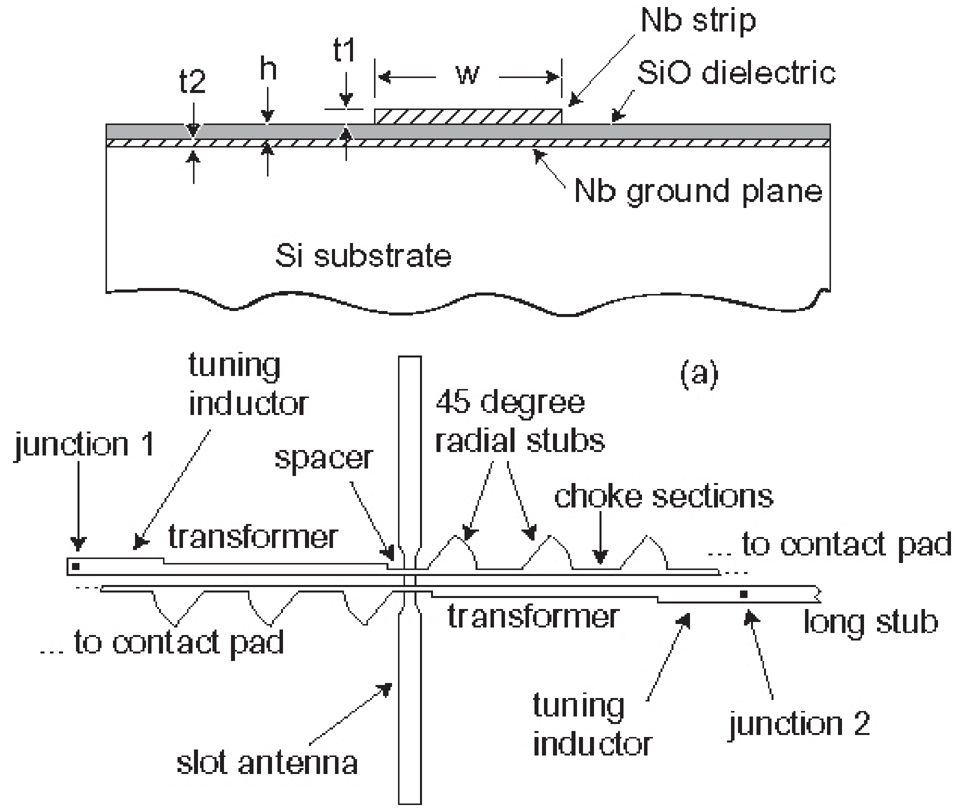


CALTECH

Precision MM-Wave Measurements of Superconducting Microstrip Lines

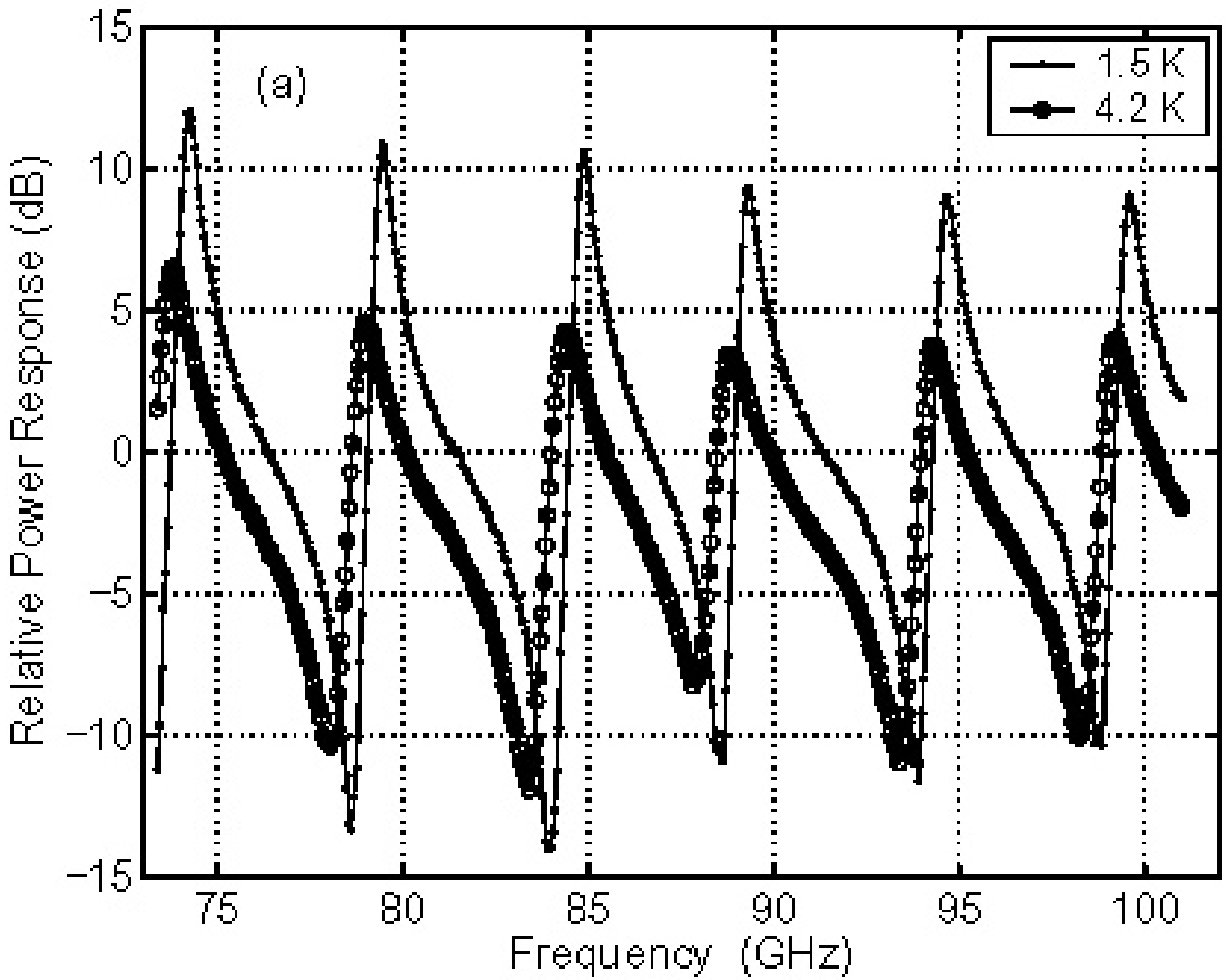
A. Vayonakis et al. (2004), submitted





100 GHz test chip with 10 mm microstrip stub

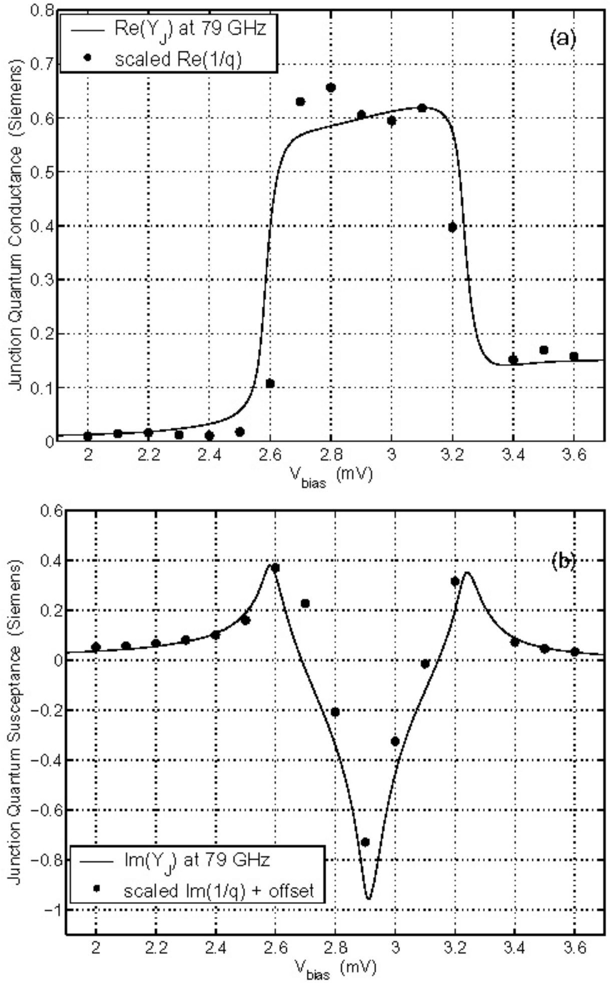
4.2 K vs. 1.5 K


(a)
1.5 K
4.2 K
Relative Power Response (dB)
Frequency (GHz)
15
10
5
0
−5
−10
−15
75
80
85
90
95
100

CALTECH

Superconducting Devices

Results: loss, phase velocity, characteristic impedance



$\overline{c}/c$ at 4.2 K	0.38234 ± 0.00010
$\overline{c}/c$ at 1.5 K	0.38346 ± 0.00010
power loss per wavelength at 4.2 K	$(1.95 \pm 0.13)\%$
power loss per wavelength at 1.5 K	$(0.58 \pm 0.16)\%$
Z_0 (Ohm)	10.8 ± 0.5

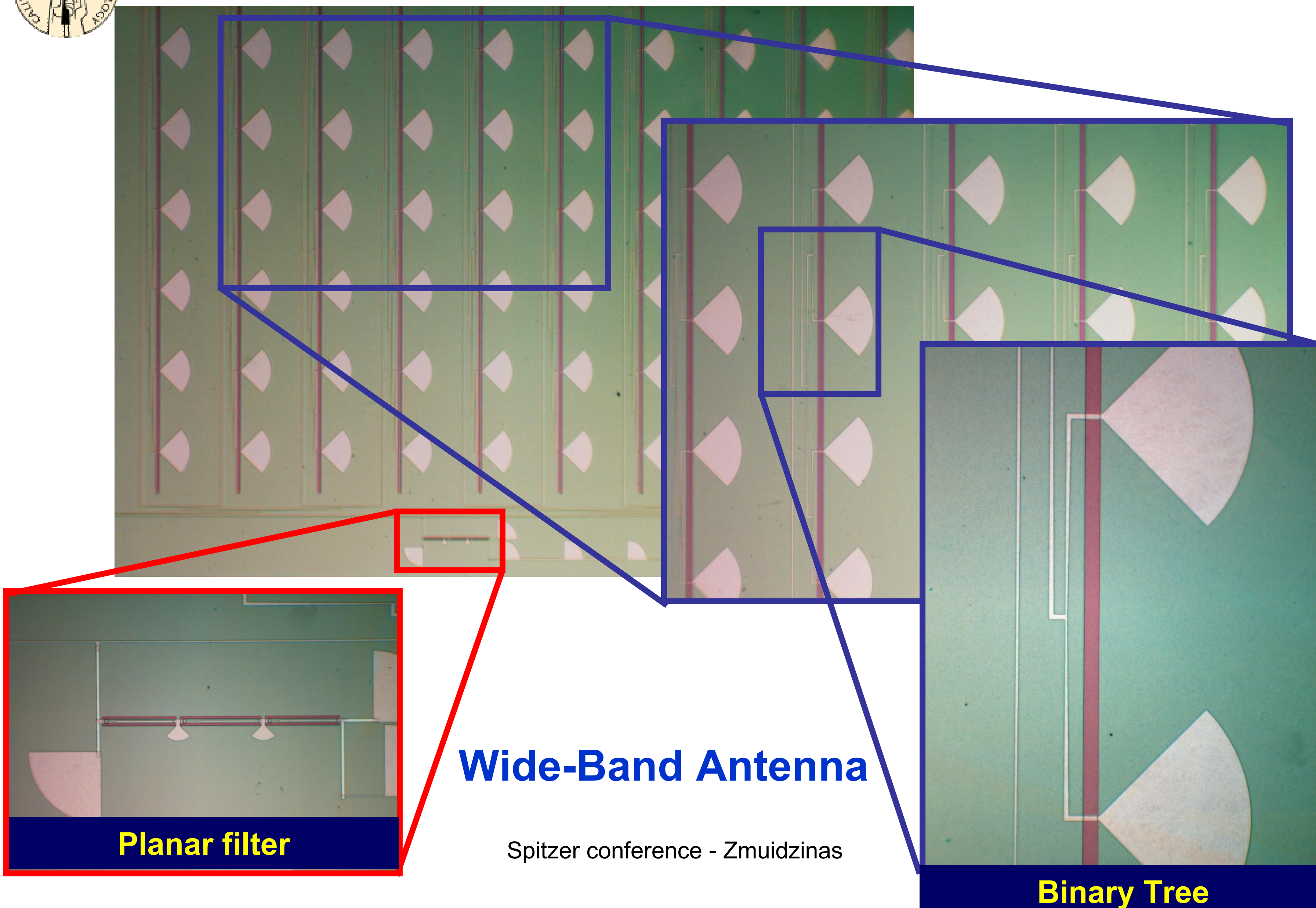
TABLE IX: Extracted physical parameters of microstrip from device #2 (100 GHz)

V_{gap} (mV)	χ^2_{min}	SiO thickness (Å)	SiO ϵ_r	SiO $\tan_\delta$ ($\times 10^{-3}$)	Nb penetration depth (Å)
2.85	3.38	3953±93	6.21±0.16	1.4±0.2	584±64
2.90	4.41	3947±93	6.17±0.16	1.5±0.2	603±66
2.95	5.56	3940±90	6.12±0.16	1.5±0.2	621±68

- 1/e attenuation length is 30 cm at 100 GHz
- Loss per wavelength is similar up to 500 GHz

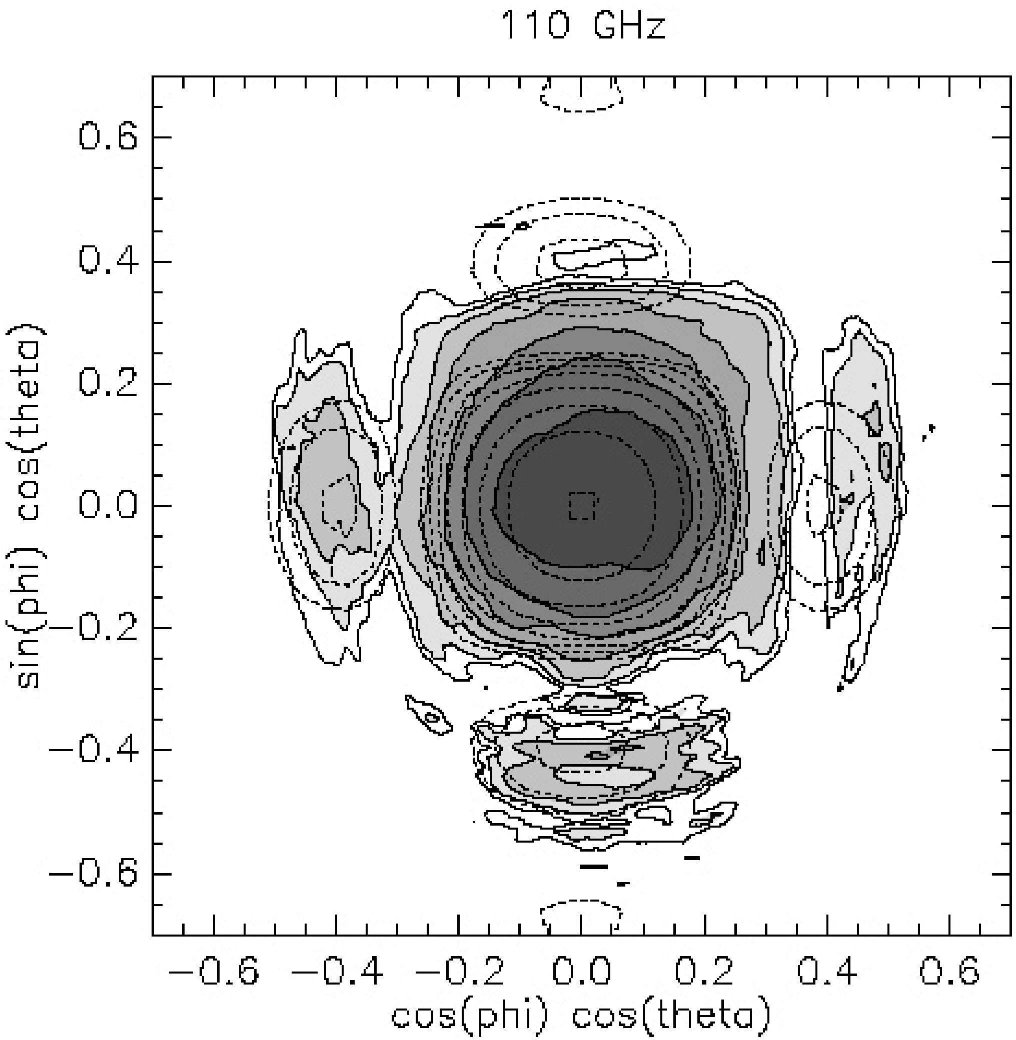
CALTECH

Superconducting Devices



Wide-Band Antenna

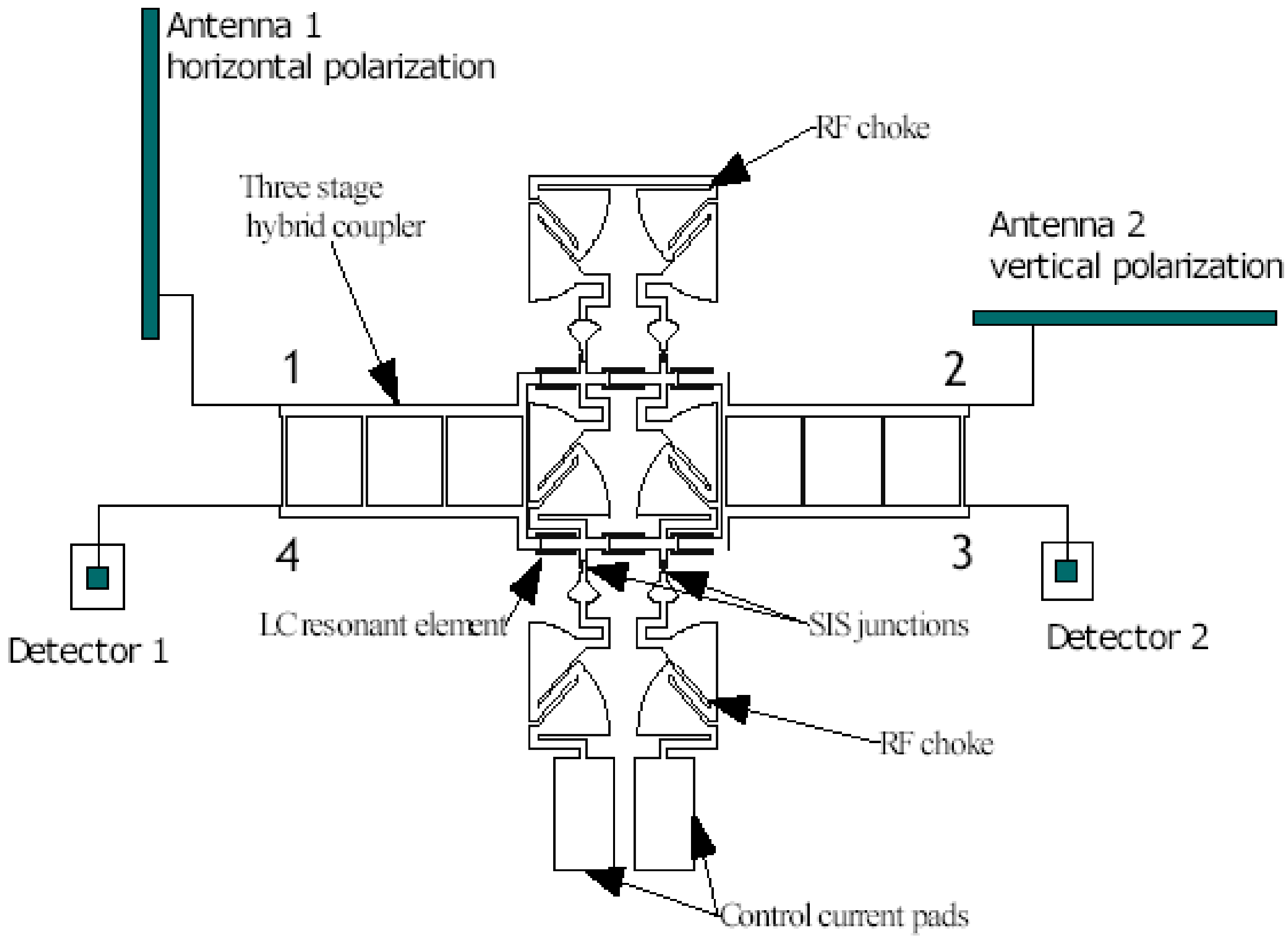
Measured antenna pattern



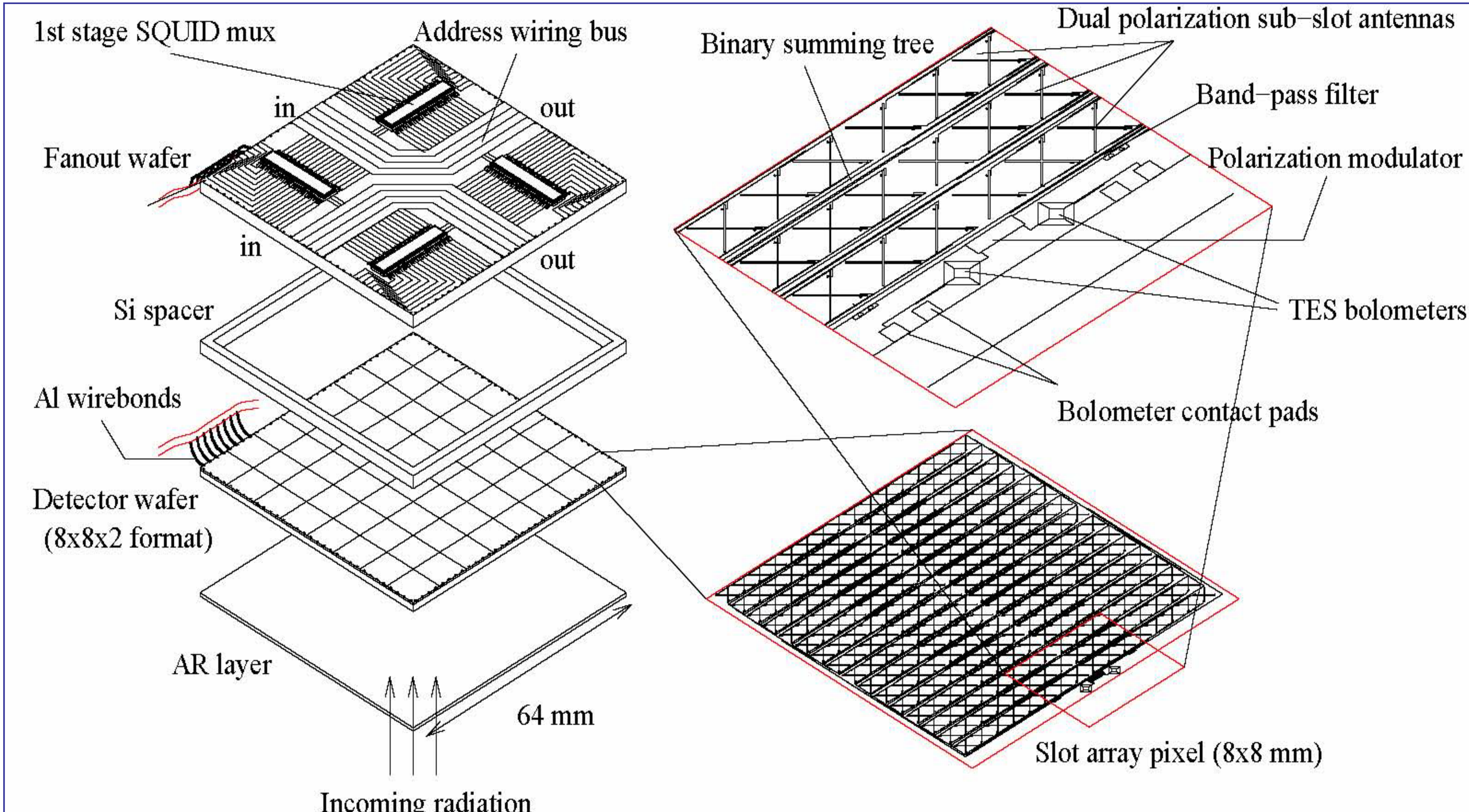
- use SIS direct detector
- 4 K testing
- silicon substrate
- quartz AR plate
- 19^{o} FWHM
- 95% main beam efficiency

Goldin et al. (2004)

Polarization modulator concept using SIS junctions



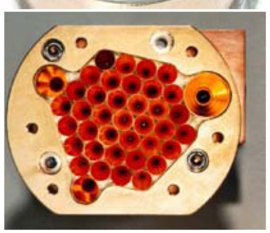
Dual-Polarization Single-Color Array Architecture



Chao-Lin Kuo and Jamie Bock

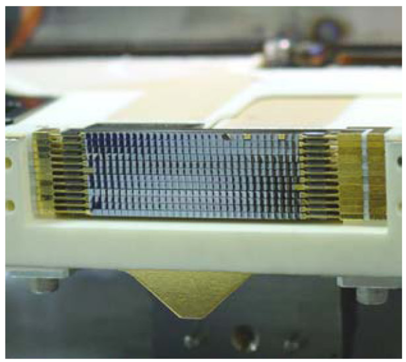
Bolometer arrays: state of the art

JCMT-SCUBA 450/850μm



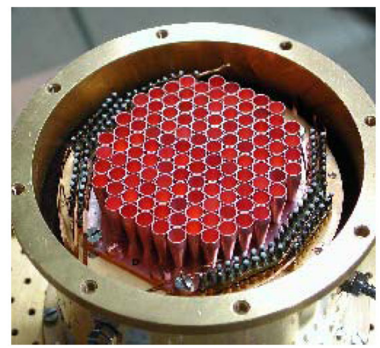
91/37 pixels
300/65mJy/√Hz

CSO-SHARCII 350μm



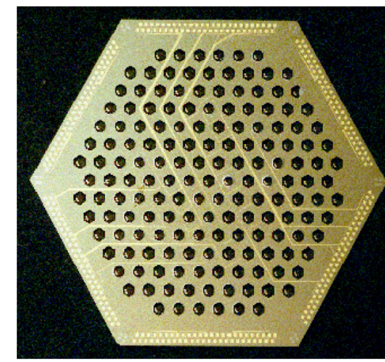
384 pixels
500mJy/√Hz

IRAM-MAMBO-2 1.2mm



117 pixels
60mJy/√Hz

CSO-BOLOCAM 1.4mm

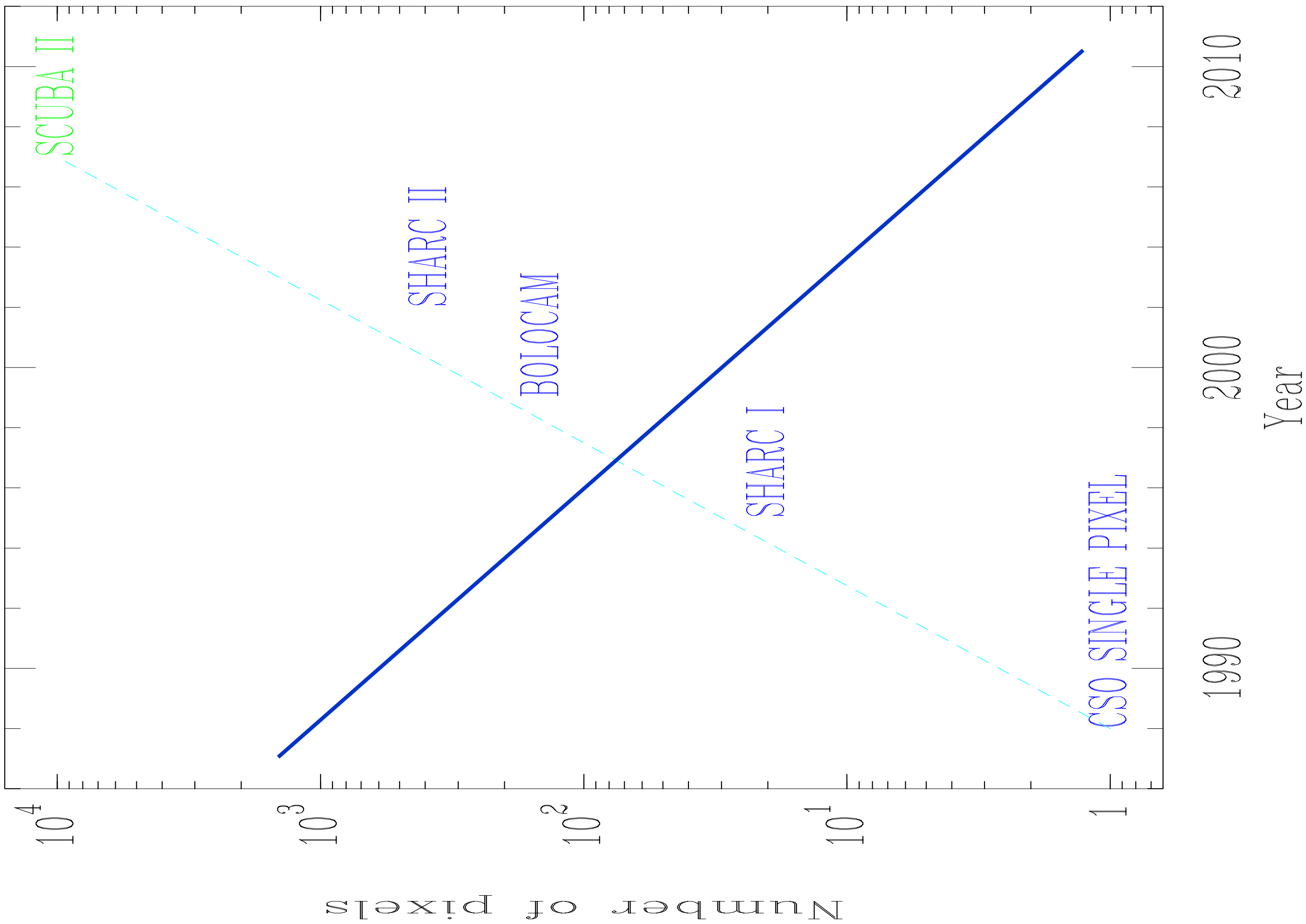


151 pixels
40mJy/√Hz

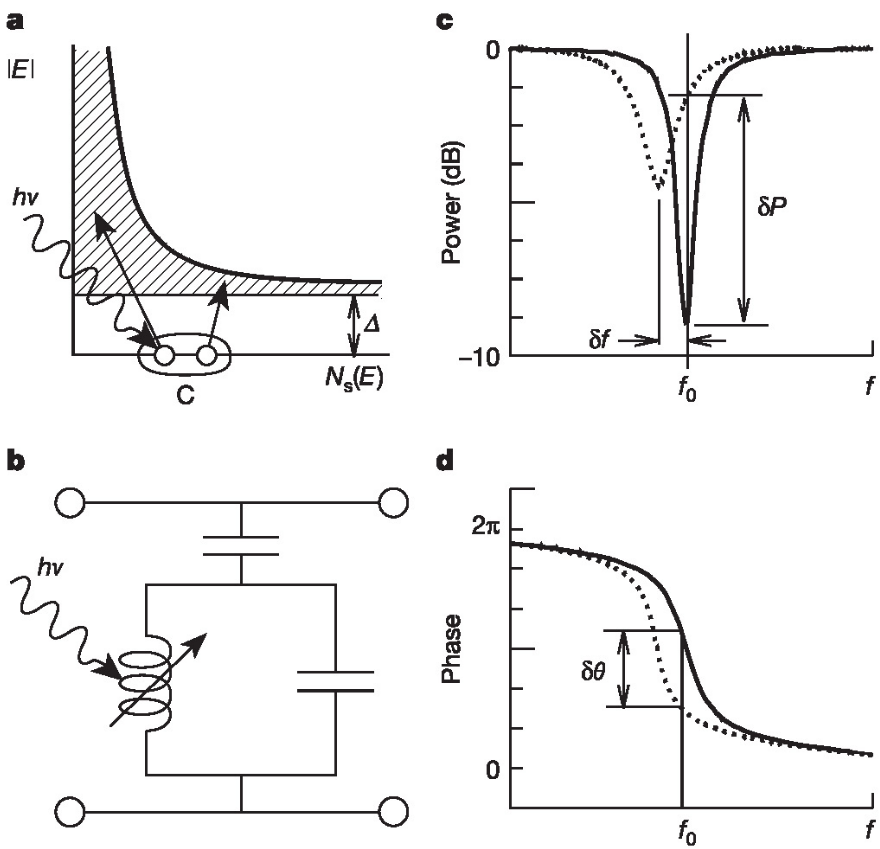
$\boxed{\text{NEP} \sim 10^{-16}\ \text{W Hz}^{-1/2}}$

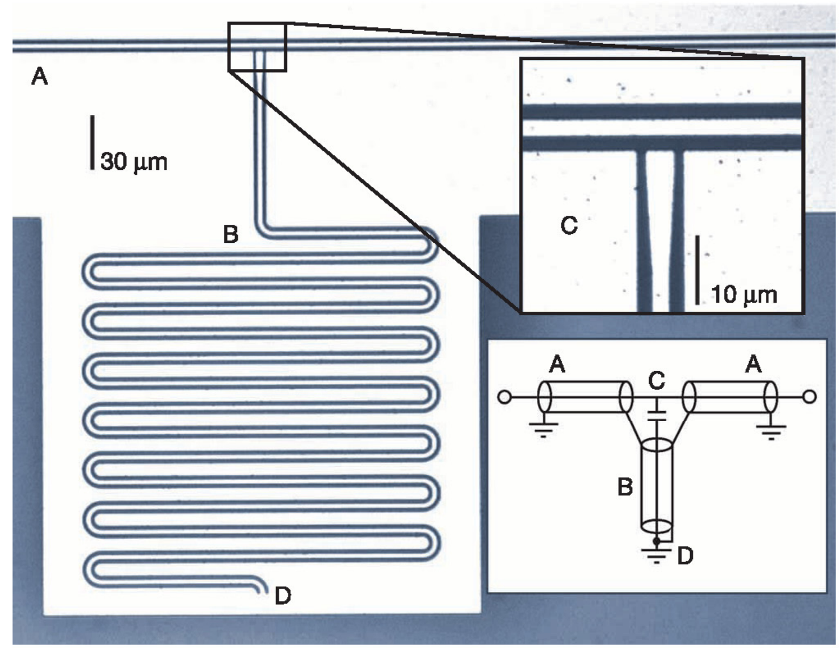
Credit: W. Holland

Array size has been following Moore's Law !



KID - a new superconducting detector





letters to nature

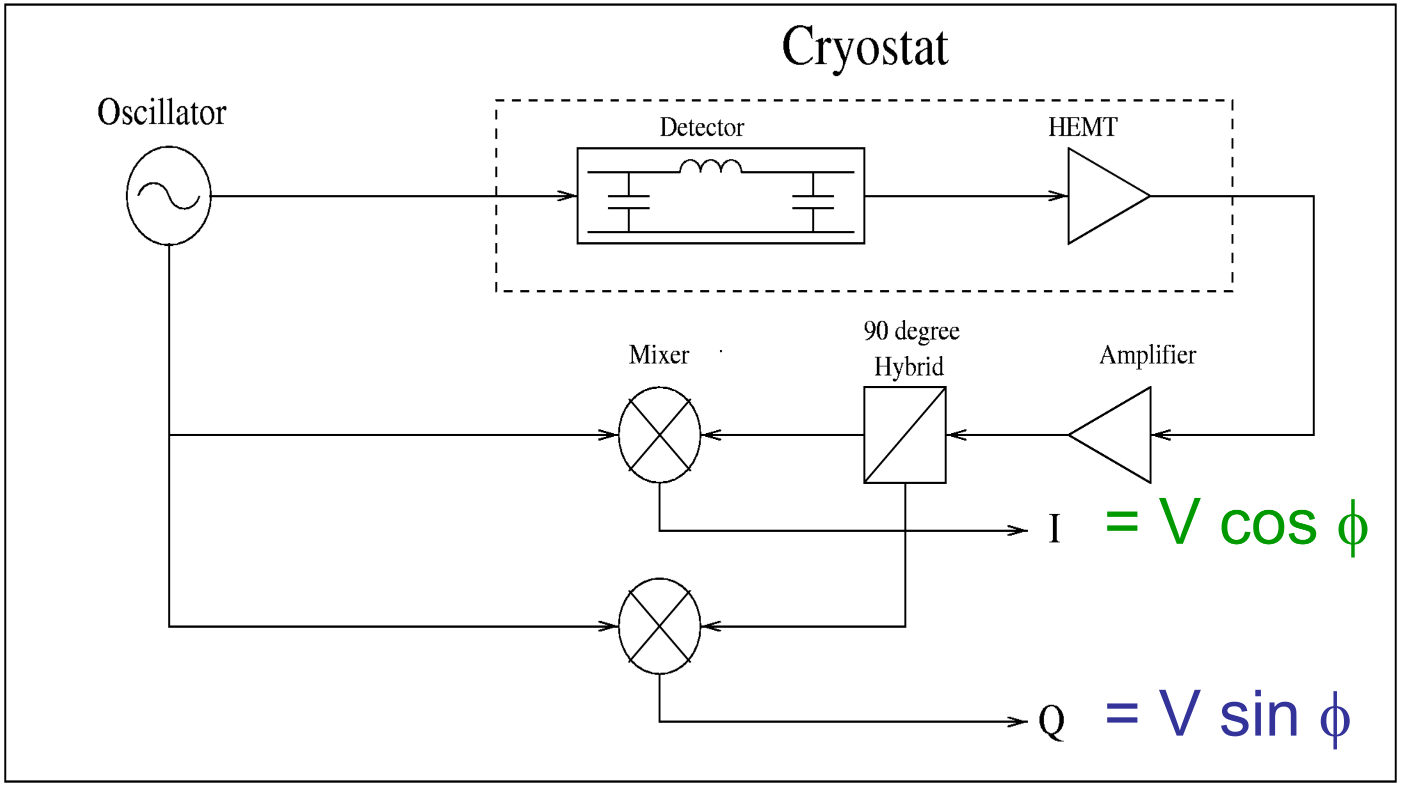
A broadband superconducting detector suitable for use in large arrays

Peter K. Day[1], Henry G. LeDuc[1], Benjamin A. Mazin[2], Anastasios Vayonakis[2] & Jonas Zmuidzinas[2]

[1]*Jet Propulsion Laboratory, Pasadena, California 91107, USA*
[2]*California Institute of Technology, 320-47, Pasadena, California 91125, USA*

Potential applications: mm-waves to X-rays

IQ readout of amplitude and phase

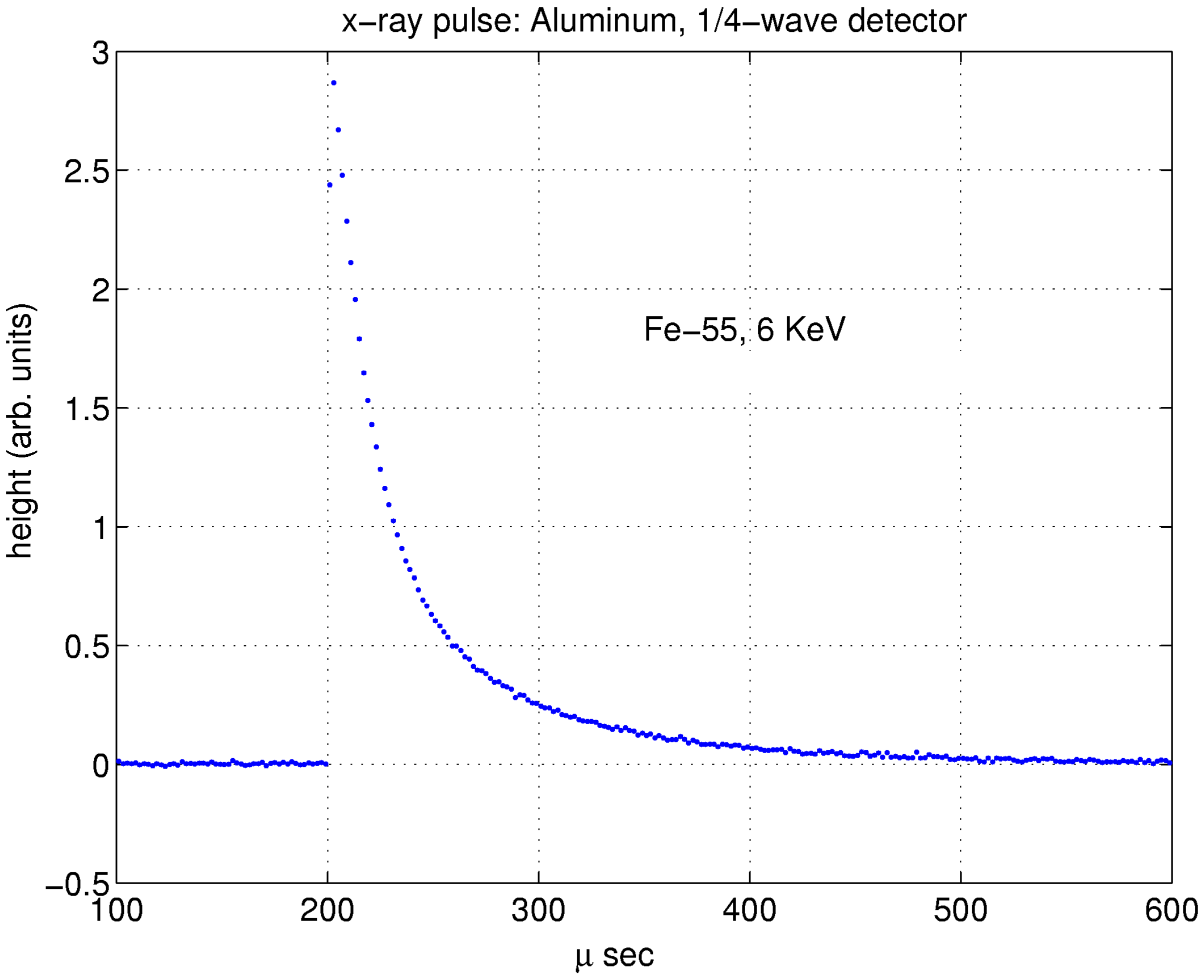


$= V \cos \phi$

$= V \sin \phi$

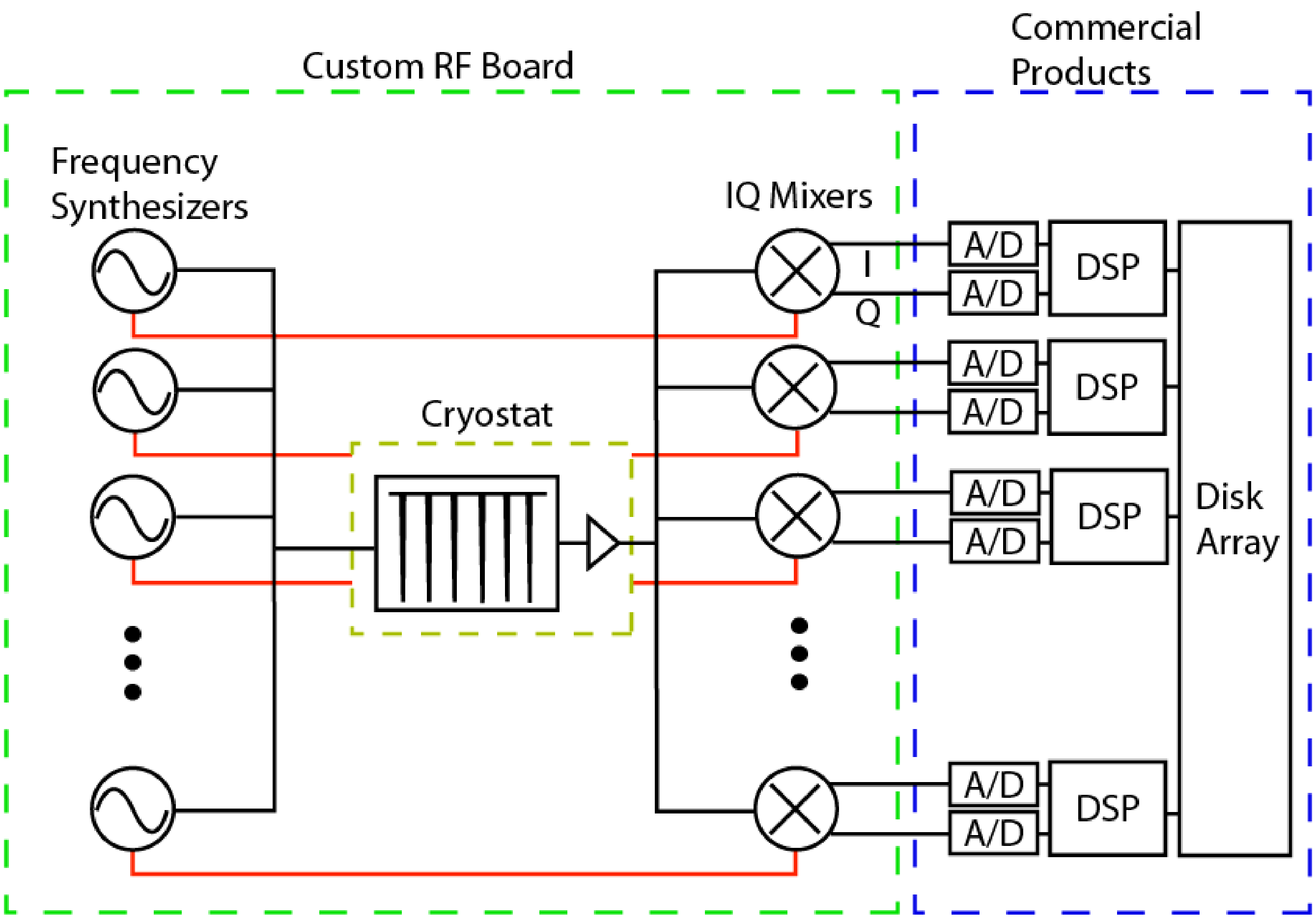
$$V \cos(\omega t - \phi) = V \cos \phi \cos \omega t + V \sin \phi \sin \omega t$$

Response to a single 6 keV X-ray photon



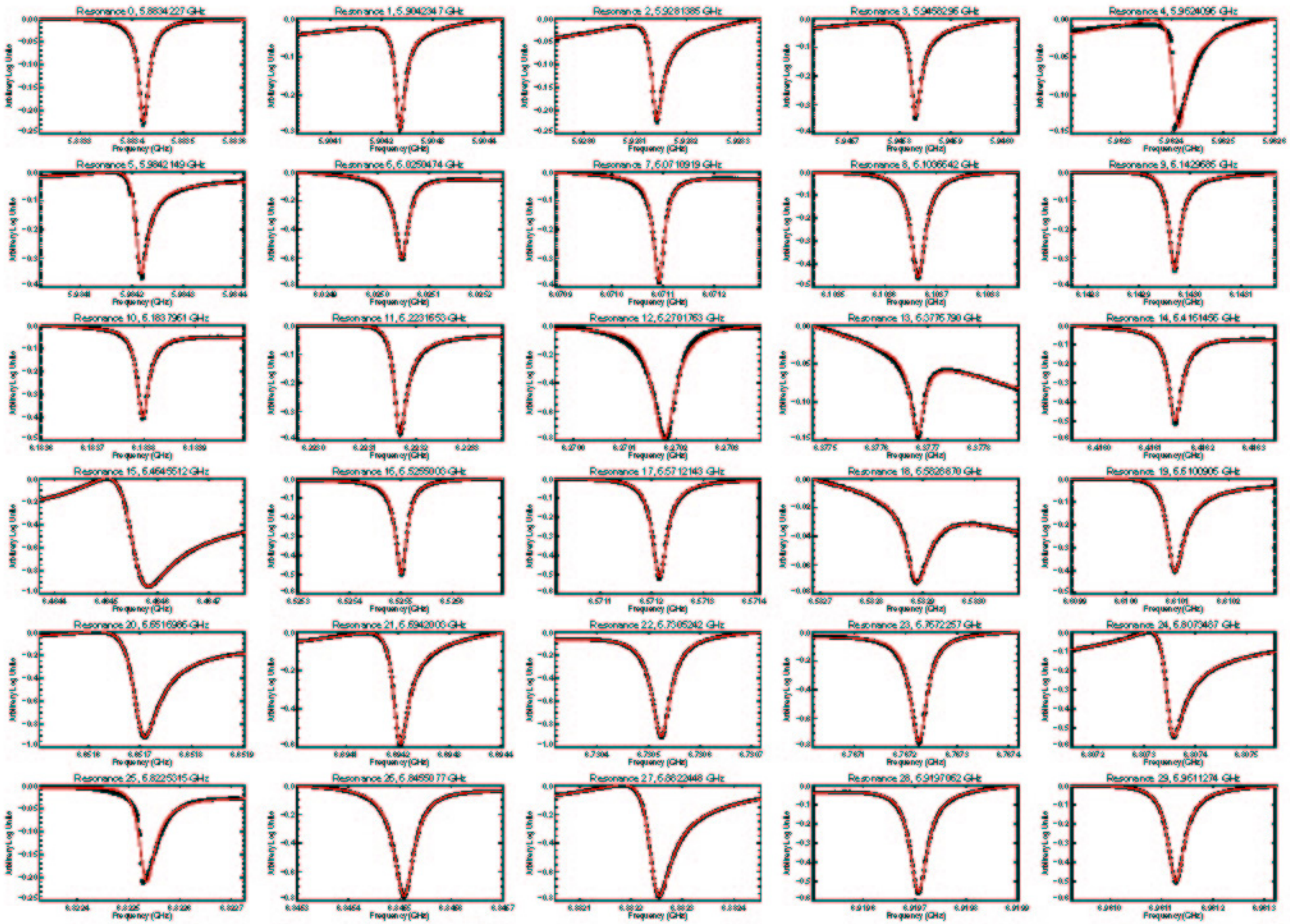
- Rise time: resonator bandwidth
- Fall time: quasiparticle decay
- Nyquist sampled readout
- High pulse SNR:
  - $\Delta E \sim 11$ eV
- Output noise spectrum measured
  - Dominated by resonator noise, originating in substrate
  - Readout NEP contribution ~10 dB lower
  - NEP ~ 10^{-16} W / $Hz^{1/2}$
  - NEP consistent with observed pulse ΔE

Frequency-domain Multiplexing



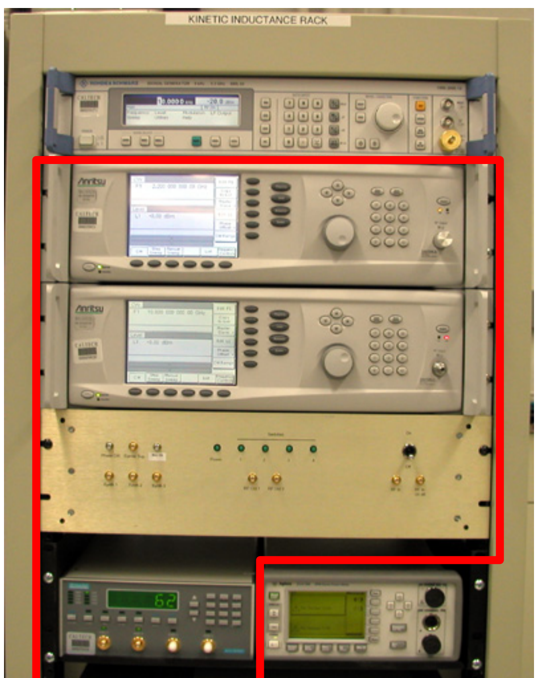
CALTECH

Measurements – 30 resonators; Q ~ 200,000

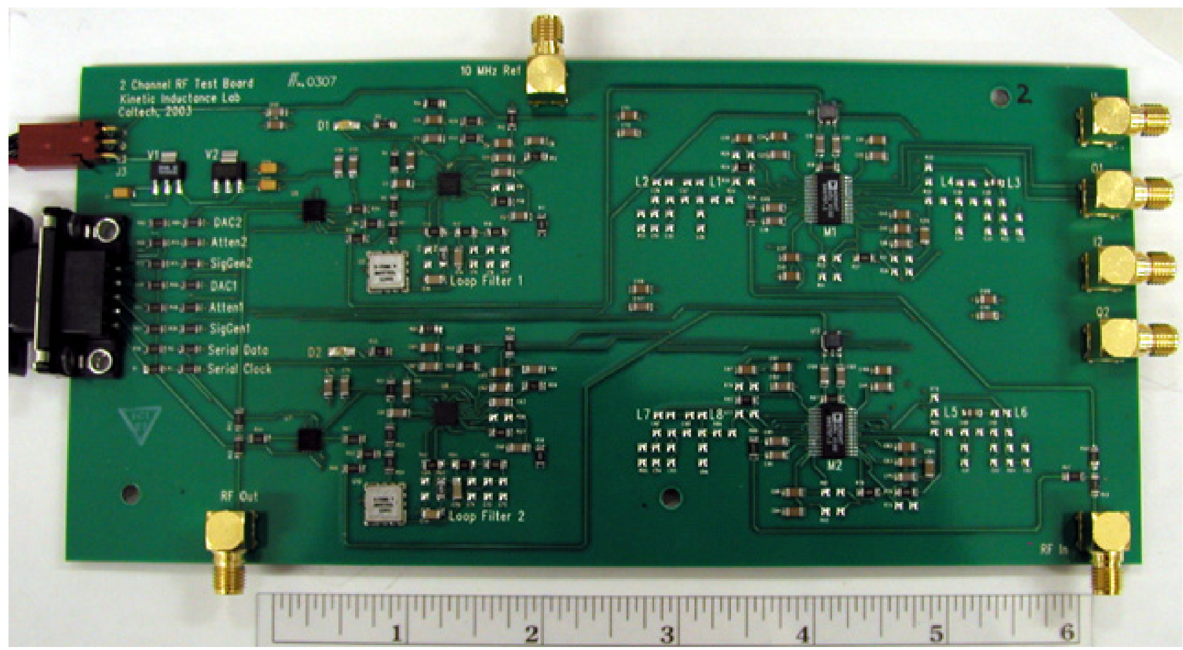


Wireless technology for KID readouts

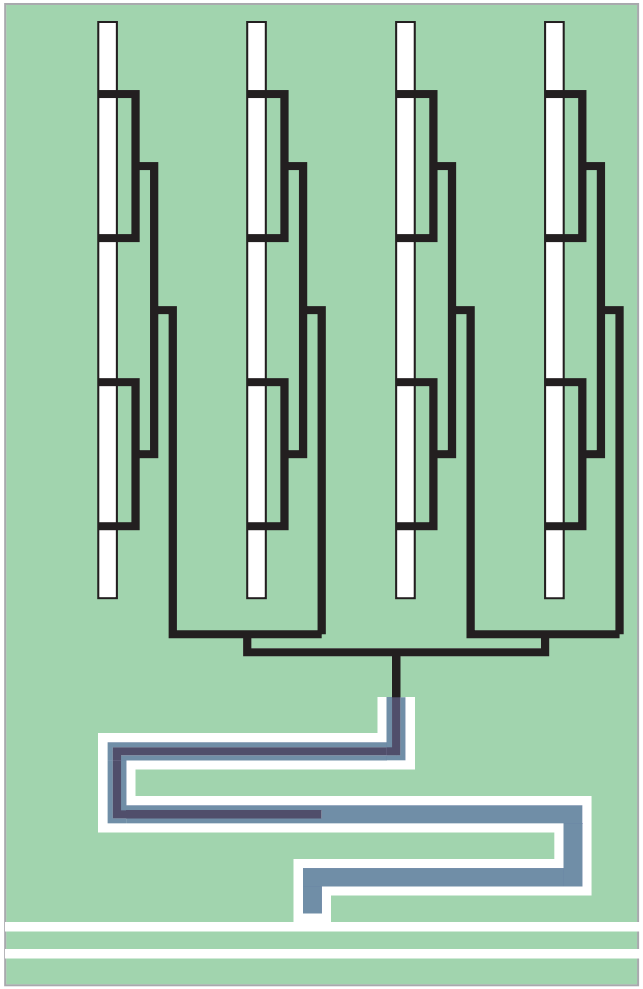
- Many readout channels can be condensed onto a single circuit board using cell phone integrated circuits
- Readout circuitry is outside the cryostat !



=

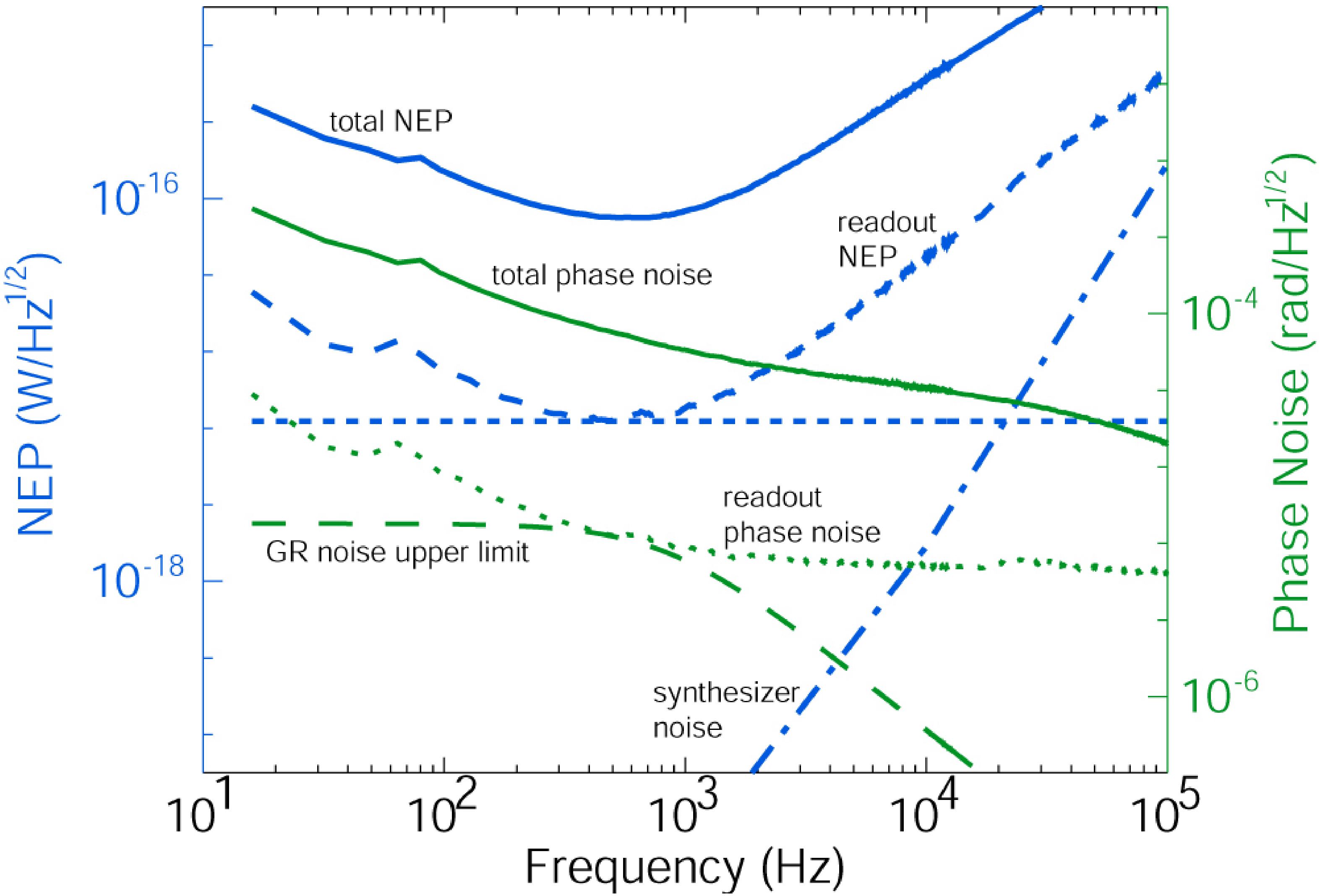


Antenna-coupled kinetic inductance detector



- *Niobium* - ground plane (green) and top microstrip conductor (black)
- *Aluminum* – center conductor of CPW KID resonator (blue)
- Simple to fabricate !
- KID is easy to couple to antenna
- *Demonstrated* NEP already useful for ground-based submm imaging
- Single-pixel lab demo in 2004 ?
- Ultimate NEP limit < 10^{-19} W/Hz$^{1/2}$

Where is the noise coming from ???

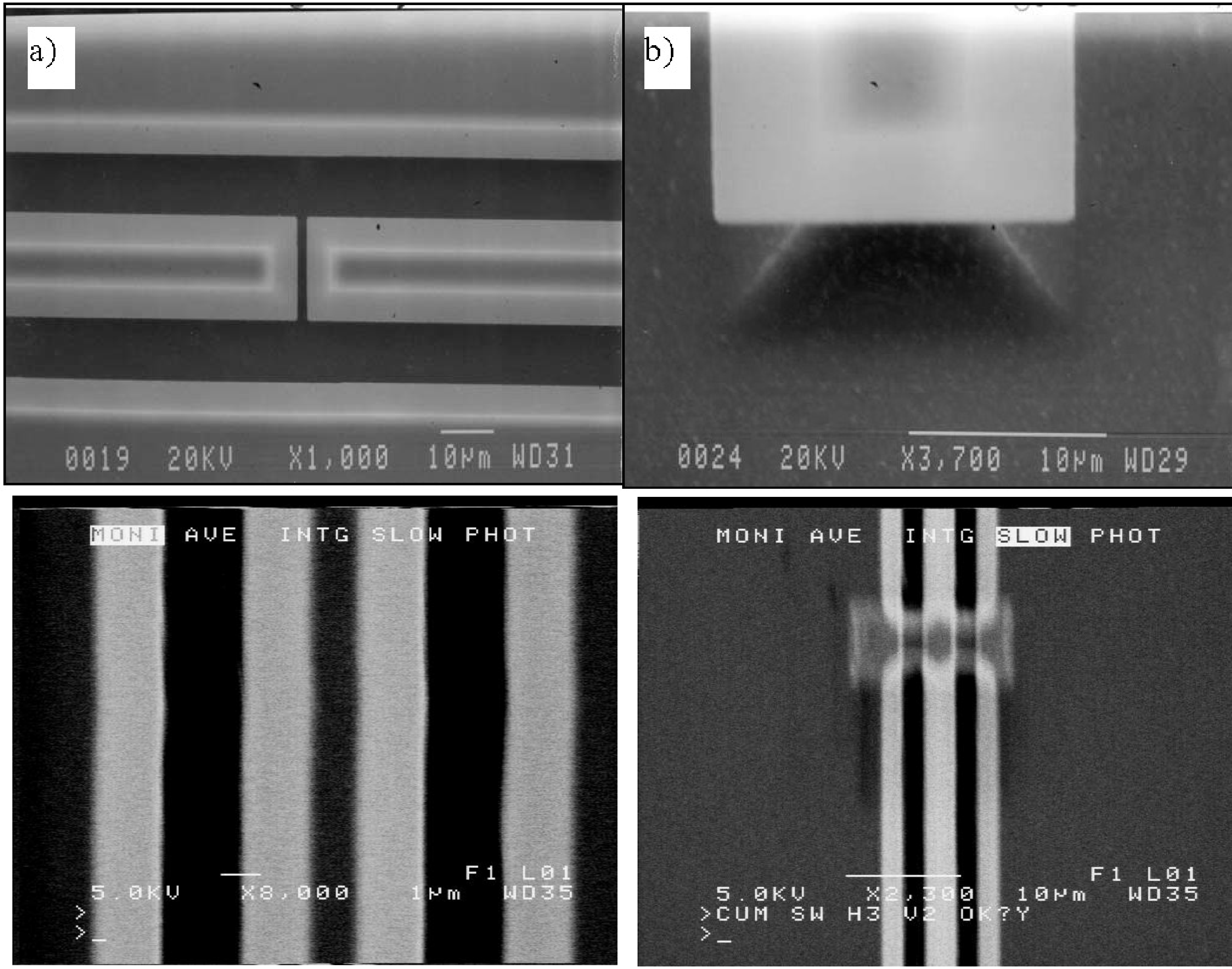


Day et al., 2003

CALTECH

Superconducting Devices

Substrate noise ?

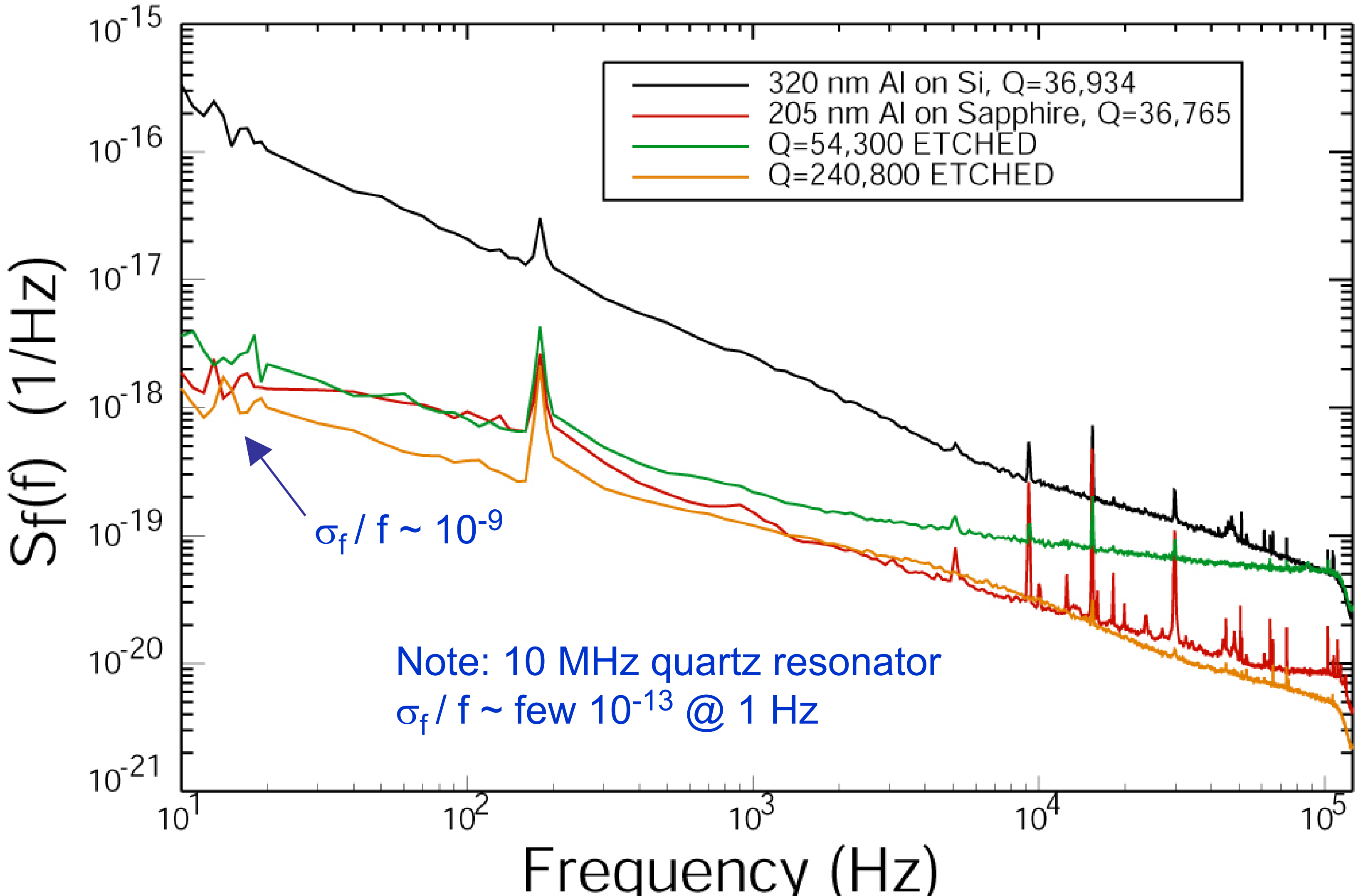


Credit: H. G. LeDuc

CALTECH

Superconducting Devices

Etching away substrate reduces noise…



Summary

- New elements for direct detection instruments
  - Low-loss transmission lines
  - Narrow-beam planar antennas
  - Planar lithographed filters
  - Microstrip-coupled bolometers
- Kinetic Inductance Detectors
  - Already interesting for ground-based submm
  - Must develop prototype arrays and readout electronics
  - Continue study of device physics, noise, materials

Conclusions

- Superconducting detectors are proving to be critical for mm/submm astronomy
  - SIS mixers
  - HEB mixers
  - TES/SQUID bolometers
  - Integrated CMB focal planes
  - KIDs

Superconducting Detectors and Mixers for Millimeter and Submillimeter Astrophysics

Jonas Zmuidzinas, *Member, IEEE* and Paul L. Richards

(Invited Paper)

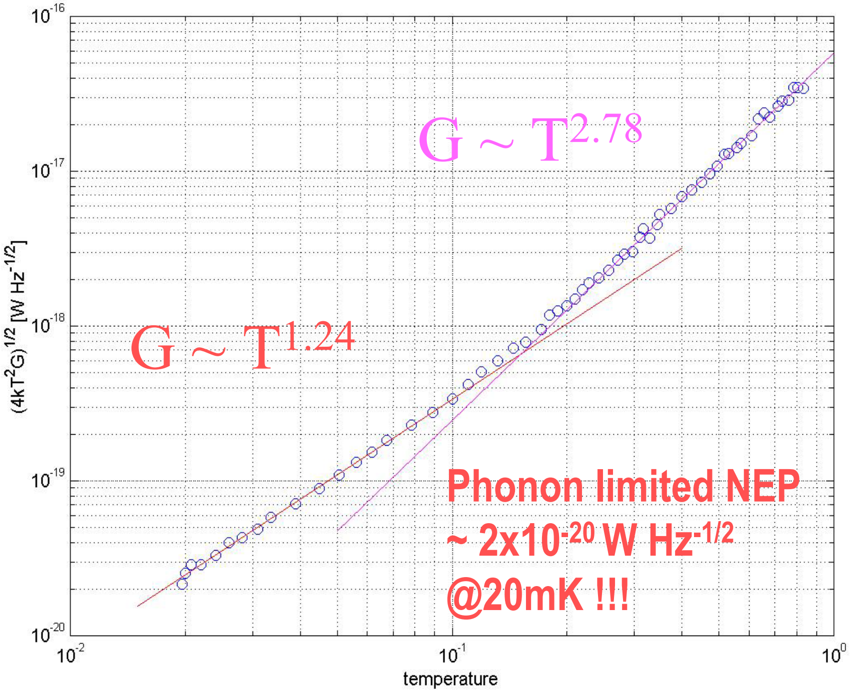
Proc. IEEE, in press

CALTECH

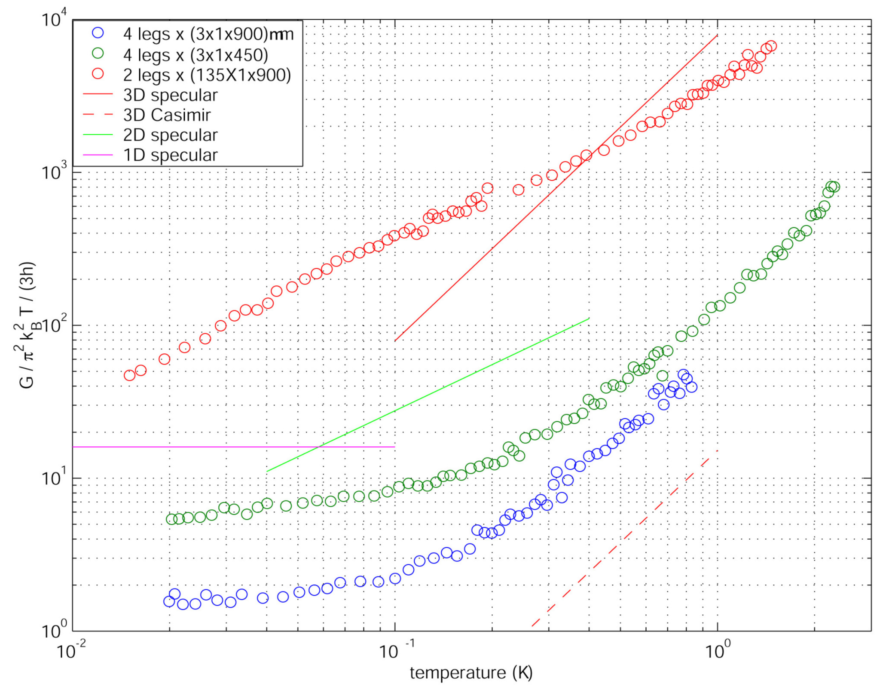
Superconducting Devices

Thermal conductance of silicon nitride at millikelvin temperatures

A)



B)



A) Thermal conductance measurement using noise thermometry. The device consists of noise thermometer, 4 SiN_x legs with dimensions (3 x 1 x 900)μm and Nb leads. There is a clear change in dimensionality of the conduction from 2d – 1d behavior.

B) Thermal conductance measurement using noise thermometry as a function of isolator geometry plotted in unit of the “quantum of thermal conductance”. In these units the flattening of the curves for the narrow legs is an indication of 1d behavior. Notice this does not occur in the wide legged device.

Data: P.Day, Fabrication: R.LeDuc, T. Jun